POWER CONTROL FOR WIND TURBINES IN WEAK GRIDS

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RISØ NATIONAL LABORATORY
THE TEST STATION FOR WIND TURBINES

Contract JOR-3-CT95-0067

PUBLISHABLE FINAL REPORT

January 1996 to December 1998

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1 Abstract

In many parts of the world and certainly in Europe large areas exist where the wind resources are good or very good and the grid is relatively weak due to a small population. In these areas the capacity of the grid can very often be a limiting factor for the exploitation of the wind resource.

There are two main problems concerned with wind power and weak grids. The first is the steady state voltage level. When the power consumption is low e.g. during the night the voltage of the grid can increase to levels above the limits if the wind power input is high. The other main problem is voltage fluctuations. Because the wind is fluctuating the output from the wind turbines is also fluctuating. This together with wind turbine cut-ins can result in voltage fluctuations that are above the flicker limit. Some or all the these problems can be avoided if a so-called power control concept is applied together with the wind farm.

The idea behind the power control concept is eliminate the violations of the steady state voltage level by buffering the power from the wind turbines in periods where the voltage limits might be violated and then release it when the voltage level is lower and combine this ability with smoothing of the power output in order to remove power fluctuations that otherwise would create voltage fluctuations above the flicker limit.

The project consists of three parts: investigation of the general applicability of the power control concept, design, implementation and testing of a battery based prototype and two case studies.

In order to assess the general applicability of the concept a framework has been formulated in which the different options (power control concepts, grid reinforcement and dumping of surplus wind energy) can be compared. As part of this, models have been developed, that can assess the voltage fluctuations and the steady state voltage behaviour for the different options. The investigations have shown that the power control concept can compete with grid reinforcement and usually the dumping of wind energy will be the most expensive option (in the case where rather large amounts of wind energy are installed).

The prototype of a socalled 'add-on' power controller has shown that it is possible to control the output from the combined system so that the fluctuation in power are much reduced and at the same time the reactive power is controlled to a desired value.

The two case studies (Madeira, Portugal and Co. Donegal, Ireland) revealed that sometimes the least cost and most attractive option is change in the operating strategy of the power system. This allowed that further wind energy can be integrated at competitive cost in the Madeira power system. In Co. Donegal the option for pumped storage are good combined with good wind resources. Unfortunately the grid is weak. The least cost option for the feeder studied is either grid reinforcement or a power control system based on pumped storage if rather large amounts of wind energy are to be absorbed by the power system. The cost estimates for the two option are in the same range.

Further work is suggested in the following areas:
- Demonstration of power control concept based on pumped storage,
- Further development of 'add-on' and 'integrated' concepts especially on the controls,
- Further development of the models needed as part of the developed framework.

2 Partnership

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3 Objectives of the Project

Presently, high wind potentials in remote areas may not be utilized for electricity production due to limited grid transmission capacity and/or difficulties in matching the electricity production with the demand. The overall project objective is to help overcome these bottlenecks, i.e. to identify and analyze methods and technologies for making it viable to utilize more of the wind potential in remote areas. The suggestion is to develop a power control concept for wind turbines which will even out the power fluctuations and make it possible to increase the wind energy penetration. The main options are to combine wind power with a pumped hydro power storage or with an AC/DC converter and battery storage. The AC/DC converter can either be an "add-on" type or it can be designed as an integrated part of a variable speed wind turbine. The idea is that combining wind power with the power control concept will make wind power more firm and possible to connect to weaker grids. So, when the concept is matured, the expectation is that for certain wind power installations, the cost of the power control is paid back as added wind power capacity value and saved grid reinforcement costs.

To assess and develop the concept, the project comprises the following four work packages:

1) Develop concept:

To develop and analyze concepts for "smart" power control of wind turbines and power systems with wind turbines. The main options are pumped storage, "add-on" or "integrated" active and reactive (PQ) power controllers. In order to analyze these options, existing models for wind turbines, power system operation and load flow must be modified and developed.

2) Test prototype:

To monitor and test an add-on PQ controller in combination with a conventional wind turbine. The suitable hardware will be supplied from ABB (NO) and installed at the Test Station for Wind Turbines, Risø (DK). The testing will include monitoring of operating conditions under real life conditions and for various control strategies.

The testing will be used to verify the models mentioned under 1) as well as to get experience with the operation and performance of the concept under real operating conditions.

3) Madeira (PT) case study:

To analyze and suggest solutions for efficient use of wind energy in the power system of Madeira (PT). At Madeira, during high wind and low load situations, the electricity production may get higher than the demand and some of the wind turbines have to be stopped to ensure power system stability. If wind energy shall supply more of the electricity consumption in the future, methods and technologies must be suggested as to better utilize the wind energy, e.g. surplus power during periods with high wind speeds and low load may be used for pumping hydro.

4) County Donegal (IE) case study:

To analyze and suggest solutions for connecting a MW sized wind farm in County Donegal (IE) to a remote grid with limited transmission capacity. County Donegal is situated in the Northwestern corner of Ireland and has excellent wind resources with many sites having excess of 8 m/s. The limiting factor for developing the wind resource is basically the weak grid. So, a study on power control for wind turbines in weak grids is utmost relevant for increasing the wind energy penetration in County Donegal.

4   Technical Description

4.1   Background

In many parts of the world and certainly in Europe large areas exist where the wind resources are good or very good and the grid is relatively weak due to a small population. In these areas the capacity of the grid can very often be a limiting factor for the exploitation of the wind resource.

There are two main problems concerned with wind power and weak grids. The first is the steady state voltage level. When the power consumption is low e.g. during the night the voltage of the grid can increase to levels above the limits if the wind power input is high. The other main problem is voltage fluctuations. Because the wind is fluctuating the output from the wind turbines is also fluctuating. This together with wind turbine cut-ins can result in voltage fluctuations that are above the flicker limit. Some or all the these problems can be avoided if a so-called power control concept is applied together with the wind farm.

The idea behind the power control concept is eliminate the violations of the steady state voltage level by buffering the power from the wind turbines in periods where the voltage limits might be violated and then release it when the voltage level is lower and combine this ability with smoothing of the power output in order to remove power fluctuations that otherwise would create voltage fluctuations above the flicker limit.

The development of such a power control concept has been the objective of the current project.

4.2 Development of power control concept

The main idea is to increase the amount of wind energy that can be absorbed by the grid at a certain point with minimum extra cost.

There exist several options that can be implemented in order to obtain a larger wind energy contribution in weak grids. These options include:
- Grid reinforcement
- Grid voltage controlled disconnection of wind turbines
- Grid voltage controlled wind power production
- Inclusion of energy buffer (storage)

Grid reinforcement increases the capacity of the grid by increasing the cross section of the cables. This is usually done by erecting a new line parallel to the existing line for some part of the distance. Because of the increased cross section the impedance of the line is reduced and therefore the voltage variations as a result of power variations are reduced. Grid reinforcement increases both the amount of wind energy that can be connected to the feeder and the maximum consumer load of the feeder. Since the line impedance is reduced, the losses of the feeder are also reduced. Grid reinforcement can be very costly and sometimes impossible due to planning restrictions.

Since grid reinforcement can be very costly or impossible other options are interesting to investigate. The most simple alternative is to stop some of the wind turbines when the voltage level is in danger of being exceeded. This can e.g. be done by the wind turbine controller monitoring the voltage level at the low voltage side of the connection point. At a certain level the wind turbine is cut off and it is then cut in again when the voltage level is below a certain limit. The limits can be pre-calculated and depends on transformer settings, line impedance and other loads of the feeder. This is a simple and crude way of ensuring that the voltage limits will not be exceeded. It can be implemented at practically no cost but not all the potentially available wind energy is utilised.

A method that is slightly more advanced is to continuously control the power output of the wind turbine in such a way that the voltage limit is not exceeded. This can be done on a wind farm level with the voltage measured made at the point of common connection. The way of controlling the power output requires that the wind turbine is capable of controlling the output (pitch or variable speed controlled) and a bit more sophisticated measuring and control equipment, but the amount of wind energy that is dumped is reduced compared to the option of switching off complete wind turbines.

The basic power control idea in the current context of this project is based on the combination on wind turbines and some energy storage. The storage is used to buffer the wind energy that cannot be feed to the grid at the point of connection without violating the voltage limits. Usually the current limit of the grid will not be critical. The energy in the storage can then be fed back to the grid at a later time when the voltage level is lower.

The situations where the voltage level will be high will occur when the consumer load of the grid is low and the wind power production is high. If the voltage level will be critically high depends on the characteristics of the grid (e.g. impedance and voltage control), the minimum load of the consumers, the amount of installed wind power and the wind conditions.

The critical issues involved in the design of a power control system are the power and energy capacity, the control bandwidth as well as investment, installation and maintenance costs. The various types of power control systems have different characteristics giving different weights on capacity, investment and maintenance.

In order to be able to assess the performance of a combined system and to determine the size the storage unit a simulation programme, SimStoree, has been developed.

SimStore is a new simulation software package, developed as a part of this project. It can simulate the steady state voltage level of a grid when both wind turbines and storage is taken into consideration.

SimStore combines a load flow calculation with a load model, a wind turbine model, storage models and control system model. SimStore then simulates a time series with a time step of e.g. 10 minutes. The main outputs are grid voltage, state of charge of storage and utilised wind energy.

The performance of a system consisting of 8*600kW wind turbines combined with a battery storage (2MW, 10MWh) connected to a weak feeder at the far end is simulated. Normal consumers are also connected to the same feeder.

In Figure 1 in the upper graph is shown the grid voltage at the point of common connection. The two lines in the graph are without storage (blue) and with storage (green). It is seen how the time in which over-voltage occur is reduced by the add-on PQ-controller. It is also seen that the size of the PQ-controller is too small to eliminate over-voltages. In the lower part of the figure is shown the amount of wind energy that has to be dumped due to the limitations of the PQ-controller.
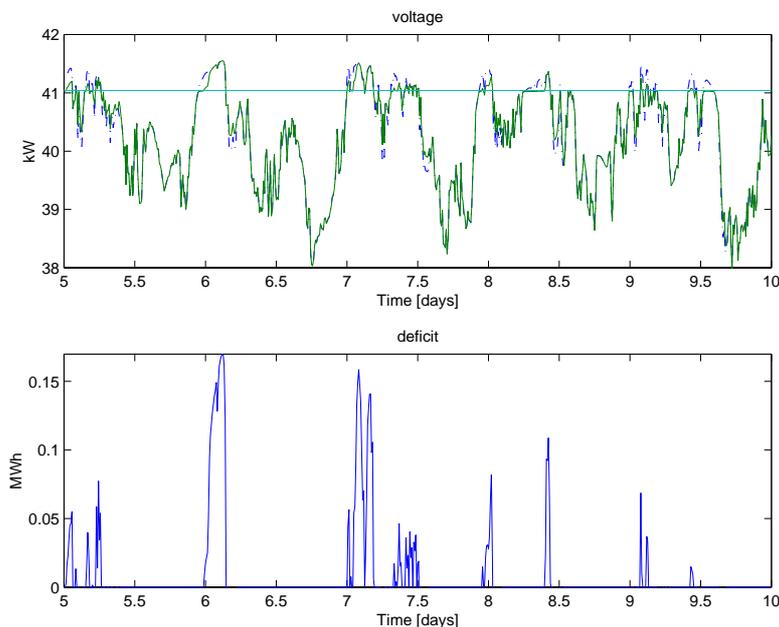

Figure 1 Voltage at point of common connection with and without PQ-controller (upper graph) and energy deficit (lower graph).

In the next figure, Figure 2, is shown the battery voltage and the State Of Charge (SOC) of the battery storage. When this figure is compared with the previous figure it is noticed that the over-voltages occur when the battery fully charged but also in situations where it is not fully charged. The reason for this is limitations in the capability of the battery to absorb power due to limitations in the current. The modelled battery voltage indicates how the voltage changes with SOC and current. Further investigations have shown that the battery voltage and the losses in the battery are inadequately modelled.
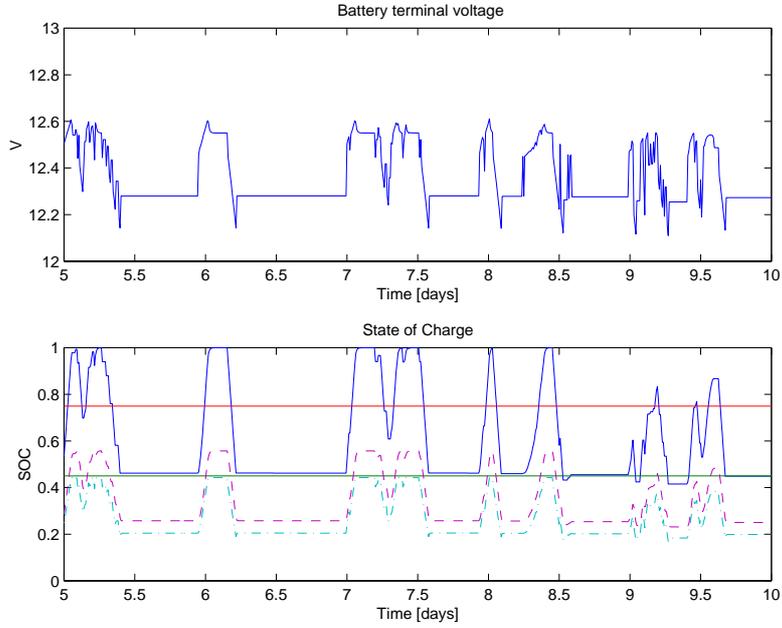
Figure 2 Battery voltage and state of charge of the two reservoirs and total.

The results from the SimStore simulations are used as the basis for an assessment of the economic performance of the combined system (both battery and pumped storage) compared with alternatives: dumping of excess wind energy and grid reinforcement.

It is assumed that the operating conditions are the same throughout the lifetime of the plant. The lifetime of the plant is 20 years. The discount rate is taken as 5% per year. This gives the annuity factor of *a=12.46*. The value of the energy is taken as $V_E=0.04$ *ECU/kWh*. This is approx. the short run marginal cost of energy from a gas turbine. The capacity credit is taken as 2/3 of the generating capacity and the investment is compared to investment in a new gas turbine plant, 670 ECU/kW. It is assumed that the batteries have a lifetime of 10 years. The cost of grid reinforcement is assumed to be in the range 20-35kECU/km. The decreased losses in the grid due to grid reinforcement are neglected.

The options compared are
- dumping wind energy when over-voltage occur
- grid reinforcement in order to avoid dumping of wind energy
- pumped storage at different sizes
- battery add-on storage at different sizes

The cases used as an example here are
- 8*600 kW wind turbines, add-on storage unit (10MWh, 2MW)
- 8*600 kW wind turbines, pumped storage unit (10MWh, 2MW)
- Grid reinforcement

Table 1 Total investment of different options to avoid over-voltage

		I_{min}	I_{max}	$I_{Rd,min}$	$I_{Rd,max}$	Capacity Credit	$I_{tot,min}$	$I_{tot,max}$
		kECU	kECU	kECU	kECU	kECU	kECU	kECU
8*600kW	No storage, no grid reinforcement	0	0	0	0	0	0	0
8*600kW	add-on (10MWh, 2MW)	650	3300	307	1842	893	64	4248
8*600kW	pumped storage (10MWh, 2MW)	1140	1700	0	0	893	247	807
8*600kW	grid reinforcement	666	1166	0	0	0	666	1166

Table 2 Total value of energy lost for different options to avoid over-voltage

		Energy stored	Energy dumped	Total for 1 year
		MWh	MWh	kECU
8*600kW	No storage, no grid reinforcement	0	2592	1292
8*600kW	add-on (10MWh, 2MW)	184	715	448
8*600kW	pumped storage (10MWh, 2MW)	560	343	450
8*600kW	grid reinforcement	0	0	0

Table 3 Total cost of different options to avoid over-voltage

		$T_{c,min}$	$T_{c,max}$
		kECU	kECU
8*600kW	No storage, no grid reinforcement	1292	1292
8*600kW	add-on (10MWh, 2MW)	512	4696
8*600kW	pumped storage (10MWh, 2MW)	697	1257
8*600kW	grid reinforcement	666	1166

The tables, Table 1-Table 3, indicate that PQ-controllers can be cost effective. In the example pumped storage is worth considering. The cost range is almost identical to the cost range of grid reinforcement. If batteries are really cheap add-on PQ-controller can be considered. Dumping of energy is the most expensive option. For large systems grid reinforcement seems to be the least cost option.

The economic estimates assume that the wind turbines are installed anyway. The investment in the wind turbines is excluded.

Different systems for controlling the power output from a wind farm connected to a weak grid have been investigated. The investigation includes development of different control strategies, use of different storage types, development of a framework for comparing different options and tools needed as part of the framework.

The investigations have shown that for small systems where only small amounts of wind energy would otherwise have been dumped add-on PQ-controllers with battery storage can be the least cost option compared to grid reinforcement and dumping of energy. For larger systems pumped storage is attractive and worth considering, but for large systems the least cost option is grid reinforcement.

4.3 Development and testing of 'Add-on' prototype

The test facility established to develop and demonstrate the 'add-on' power control concept consists of:
- 55kW stall controlled wind turbine
- 50kVA, 30kWh battery storage system with controller
- main switch board
- control system of total system
- data acquisition system
- sensors etc.

The control and data acquisition system is shown as block diagram in Figure 3.
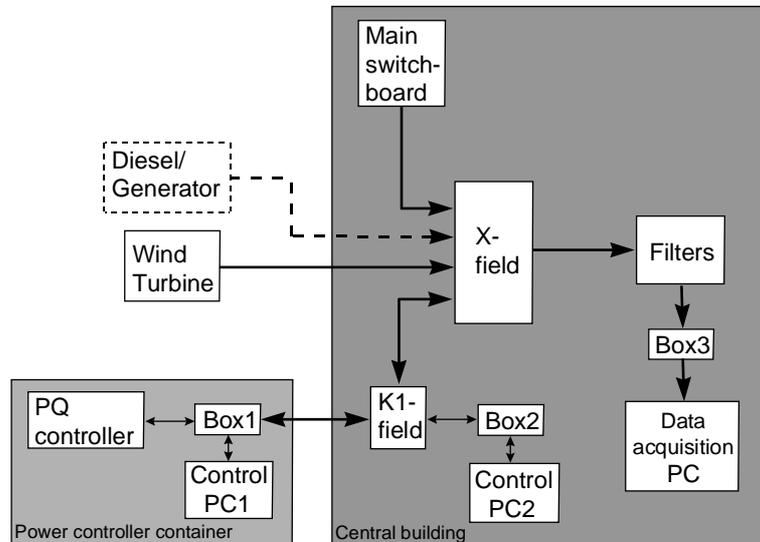
Figure 3. Power controller test facility at Risø.Control and data acquisition system

The input signals to the overall control system are:

- wind turbine output (active and reactive power)
- PQ-controller output (active and reactive power)
- Grid voltage
- Battery voltage and current
- Battery status (voltage high or low)

The signal to the data acquisition system includes also:
- total system output (active and reactive power)
- wind speed
- power controller active and reactive power command signal
- Grid frequency

The sampling frequency of the controller is 10Hz. The data is logged with 32Hz.

The first tests with the PQ-controller showed that there were large fluctuations on the power output. These fluctuations were due to the limitations on the PQ-controller hardware. In order to reduce the impact from these fluctuations a filter was implemented in the feed forward path of the control system, Figure 4. This filter cuts off the unwanted high frequency fluctuations from the output. The result is a slower system but without the filter the system is not stable.
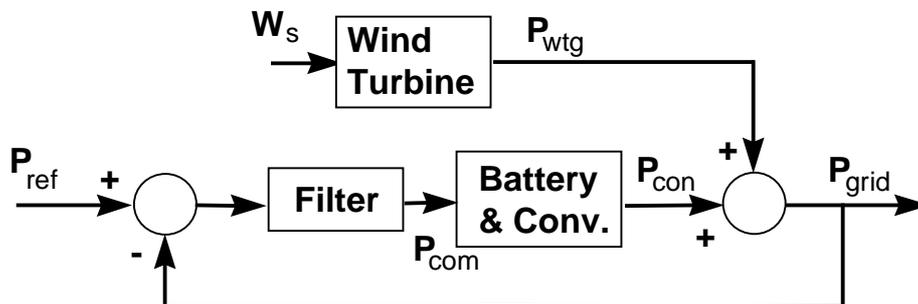

Figure 4. Low pass filter applied in the closed loop control strategy for the add-on power controller.
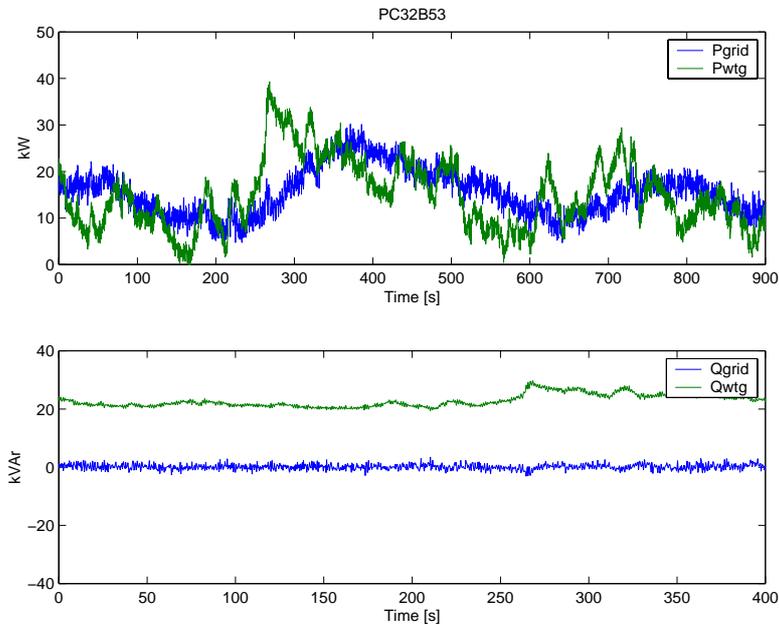
Figure 5 PQ-controller controlling active and reactive power. The active power reference is the 120s moving average of the wind turbine power.

Power smoothing operation is shown in Figure 5. Here the reference to the PQ-controller is the 120s moving average of the power output from the wind turbine. It is clearly seen how the PQ-controller reduces the fluctuations in the power output from the wind turbine. If the control hardware of the frequency converter was improved the performance would be very good and it could eliminate the flicker from the wind turbine with a minimal storage capacity.

An add-on PQ-controller has been implemented. The performance of the basic battery storage results in fluctuations of the active and reactive power output and a rather slow system due to the limitations of the controller hardware. Even with these limitations it has been shown that concept can be used to control the active and reactive power output from a wind turbine and therefore reduce the impact of the wind turbine on the grid. This will enable connection of more wind power to a weak grid without requiring grid reinforcement and the combined system contributes to the generating capacity.

4.4   Case study: Madeira, Portugal

The power system of Madeira is an island grid. The power supply system of Madeira consists of approx. 111 MW of heavy fuel diesel generator sets and 49 MW of pelton turbine hydro power plants (status 1994, assuming $\cos\varphi = 0.8$).
The hydro power plants utilise a system of water channels (levadas) which collect the rain water. The water channels are not only utilised for the hydro power plants, but also for irrigation purposes. The power transmission take place at 60 and 30 kV. The power is distributed to the consumers in the area via 6.6 kV feeders and 6.6/0.4 kV transformers.

Considering the favourable wind resources at Madeira with sites with annual average wind speeds up to 8 m/s in 10 m height above ground level (agl), and that the potential for expanding the power supply capacity with hydro power is limited, future increase in the wind power capacity at Madeira is an obvious method for meeting the future energy demand. Certainly, a number of wind farm projects are already initiated. The wind farm projects are:

1. Paul Da Serra: private 4.44 MW wind farm consisting of 33 wind turbines each rated 150 kW and 3 wind turbines each rated 130 kW.
2. Canical: private 0.9 MW wind farm consisting of 6 wind turbines each rated 150 kW.

The wind turbines for both wind farms are Nordtank (NTK) machines with fixed speed and stall control.

The impact of an additional 1.2MW wind farm at Canical is investigated from a power system operation point of view and a dynamic voltage stability point of view. The power system operation analysis is simulated using WINSYS a simulation programme for simulating the performance of a power system in terms of fuel saving etc. of power supply systems with wind energy. The dynamic voltage analysis is carried out using the INPark dynamic wind farm simulation programme. It is capable of simulating the dynamic behaviour of voltage, current etc. of a wind farm.

WINSYS requires the wind speed distribution to be represented by Weibull scale and shape parameters for each of the seasons of the year and further subdivided into the 24 hours of the average day in each season. The annual wind speed distribution at Canical is according to Gerd Spenk (1990) fitting a Weibull distribution with scale 7.4 m/s and shape 2.3 at 10 m above ground level.

The wind power output reduces the load at the diesel generator sets and consequently the fuel consumption is reduced according to the operation strategy of the diesel generators power plant and the diesel generator fuel consumption curve. In average, i.e. the annual fuel savings levelised over the lifetime of the new wind power installation, the simulation results show that the new wind power installation saves about 770 tonnes of heavy fuel per year, or in other words 213 g per kWh of wind energy output. Since the heavy fuel turbines are less efficient at low load operation, the annual fuel savings would have been higher in case the assumed load pattern had had a higher minimum load or in case the load in general had been assumed to be higher.
All results in this section refers to fixed currency of 1997 with an exchange rate of 25 PTE for 1 DKK.

WINSYS calculates the economic cost of wind energy as the levelised production cost, LPC. With the assumed 7 % p.a. discount rate and a 20 years payback period, the LPC of the assessed new wind power installation is found to be 0.31 DKK/kWh. Of this, the investment accounts for 0.26 DKK/kWh, the O&M for 0.05 DKK/kWh and the retrofit for 0.01 DKK/kWh.

The levelised operating cost of the conventional system is calculated to be 0.35 DKK/kWh, of which 0.28 DKK/kWh is for fuel and 0.07 DKK/kWh is for non fuel O&M.

The simulation results show that the levelised annual savings in fuel and non fuel O&M due to the new wind power installation can be anticipated to be about 1.0 mill. DKK. This saving together with the capacity credit of 25 % corresponding to a present value of about 1.8 mill. DKK or an annualised value of 0.2 mill. DKK, gives in total a net profit of 0.04 mill. DKK/year at the assumed 7 % discount rate. Economic break even is achieved for the internal rate of return (IRR) of 7.6 % p.a.

The impact on the voltage fluctuations of both the existing 0.9MW wind farm and the combined 2.1MW wind farm is simulated using the simulation package INPark.

The analysis of the INPark results on the dynamic simulation of Caniçal wind park and equivalent local grid behaviour, indicates the possibility to increase the wind power penetration at the Caniçal substation.

The three scenarios of Table 4 were selected for numerical simulation. These correspond to the global combination of parameters (local loads values, wind speed and the system short circuit power - S_K) that lead to favourable condition for both power stability and voltage quality (Scenario A), medium conditions (Scenario B) and the most critical conditions (low local loads, minimum S_K and nominal operation of wind park) that are illustrated by Scenario C. The maximum and minimum three-phase S_K values for Caniçal substation (taken as the PCC) are respectively 131 MVA and 79 MVA.

Table 4 Scenarios studied for dynamic voltage behaviour

	Power System S_k	Wind speed [m/s]	Local Loads	Voltage regulation [%]
Scenario A (Favourable)	max.	8	100%	+3
Scenario B (Medium)	min.	12	50%	+3
Scenario C (Critical)	min.	12	10%	+3

The emphasis is on the scenarios B and C.

The fact that the local loads have the capacity to absorb all the power generated by the park contributes significantly to the favourable voltage profile of the local grid. However, before final conclusions can be drawn, a more detailed analysis of the park should be performed. The transformers resistance - currently neglected- must be included in order to correctly identify the amplification effect on the voltage fluctuations of the park 6.6 kV interconnection busbar. Different combinations of lower load values and higher wind velocity should be simulated to assess the complete operation conditions of the local grid system.

In Figure 6 it is possible to observe the positive effect of the local loads in this weak grid. Namely from scenario B to C where the load is reduced from 50 % to 10 % of its nominal value, the voltage regulation should be operated due to the overvoltages in the wind park busbar.
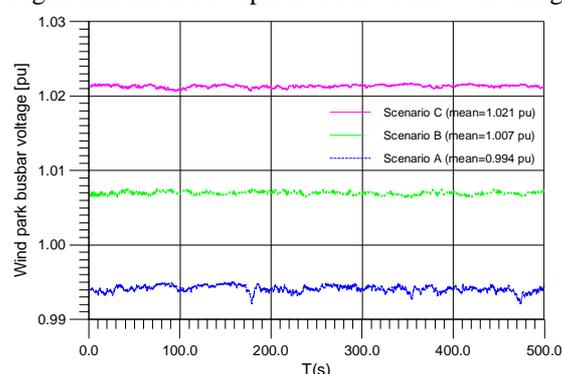

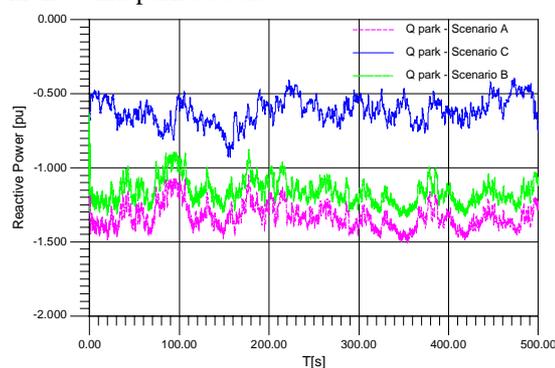*Figure 6 Voltage fluctuations in the existing wind park busbar for scenarios A, B, and C.*

Figure 7 Reactive power flow in the wind park.

The analysis of the INPark results indicates the possibility to increase the wind power penetration at the Caniçal substation. The fact that the local loads can absorb all the power generated by the park and the interconnection substation transformer has load voltage regulation (LTC) contributes significantly to the favourable voltage profile of the local grid, though the high turbulence intensity is expected to lead to frequent operation of the tap-changer of the transformer located in Caniçal substation.

The previous information on the possibility of Caniçal substation to accept extra wind power and the favourable economics of an extra 1.2 MW installation, lead to the application of INPARK to simulate the dynamic behaviour of the new Caniçal wind park (0.9MW + 1.2 MW under study). For simplicity reasons all turbines were considered of the same type. The local consumers and the grid (reinforced to have the requested transmission capacity) were simulated according to the conditions of Scenario C of Table 4 (with no voltage regulation). In Figure 9 the Caniçal local grid voltage profile for new park capacity is displayed. Figure 9 represents the active and reactive power flow in the wind park busbar.
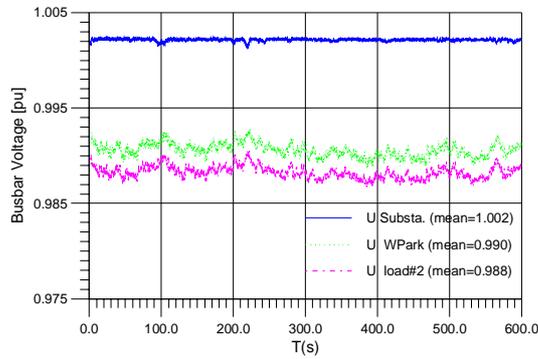
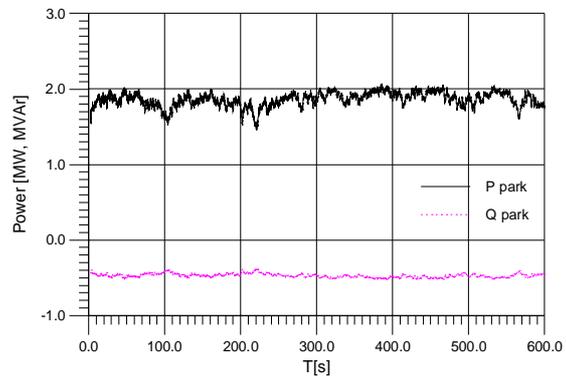Figure 8 Wind park local grid voltage profile (p.u.).

Figure 9 Total wind park active power output and reactive power flow on the wind park busbar.

INPark active and reactive power output (Figure 9) enables to estimate the short term flicker emission (P_{st}). This was computed using the Risø/DEFU method and code [Sorensen, 1995] according to the IEC Publication 868 and Ammendment 1 [IEC, 1986; IEC, 1990]. For the 30 kV side of Caniçal substation and the grid impedance computed by the Madeira power flow and short circuit analysis, the P_{st} value obtained was 0.16.

The analysis and assessment have shown that an additional wind farm with a capacity of 1.2MW can be installed at the site of the existing wind farm at Canical without exceeding steady state voltage limits.

A detailed dynamical analysis did also show that the dynamic impact from the fluctuating wind power on the grid voltage did not cause fluctuations in the grid voltage outside the limits.

The energy produced by an additional 1.2 MW wind farm can be absorbed by the power system. Simulation of the power system operation did further show that a wind farm of such a size would reduce the generating cost of energy.

The assessment of the social and environmental impact of the new wind farm showed that the negative impact on the environment would be minimal in terms of visual impact etc. and that the wind energy would save the atmosphere from carbon dioxide and other pollutants and that it would have a positive impact on the economy.

It can be concluded that an additional wind farm of 1.2MW at Canical would be a good investment. It is therefore recommended that the wind farm will be installed.

4.5 Case study: County Donegal, Ireland

The power system of County Donegal is interconnected with the national grid of Ireland. The power supply system of Ireland consists of 220 MW of hydro power plants, a pumped storage unit of 292 MW and 3540 MW of thermal power plants (status 1992). The power transmission take place at 400, 220, 110 and 38 kV. County Donegal is connected to the national grid via a 110/38 kV sub-station at Letterkenny and a 110/38 kV sub-station at Binbane. The County Donegal grid consists of three 38 kV circuits:

1. Coastal circuit between Letterkenny and Binbane.
2. Inland circuit between Letterkenny and Binbane via Stranorlar.
3. Inishowen circuit from Letterkenny to Buncrana, Cardonagh and Moville.

The power is distributed to the consumers in the area via 10 kV feeders and 10/0.4 kV transformers. New power generation units like wind turbines are required by the utility to be connected to the 38 kV line with a separate transformer.

Considering the favourable wind resources in County Donegal with sites with annual average wind speeds above 8 m/s in 10 m height, and that the potential for expanding the power supply capacity with

hydro power is limited, future increase in the wind power capacity in County Donegal is an obvious method for meeting the future energy demand. Certainly, a number of wind farm projects are already initiated.

In the current project focus has been on the first 38kV circuit (Coastal circuit).

The voltage limits for the 38kV network are 38kV±8%.

The several scenarios have been investigated. Emphasis in this section is on the case including 11*600kW wind turbine capacity, Table 5.

Table 5 Selected scenarios investigated for the Donegal case.

	Wind Turbine Capacity	Pumped Storage	Grid Reinforcement	Comments
Base Case	5*600kW	-	-	Current situation
Pumped storage @ Gweedore (Lough Altan)	11*600kW	-	-	
	11*600kW	5MW, 64 MWh	-	
	11*600kW	-	15.7+17.6km	
Pumped storage @ Ballykeeran (Lough Salt)	8*600kW	-	-	
	8*600kW	8MW, 48 MWh	-	
	8*600kW	-	15.7km	

The size of the wind farms have been chosen so that the energy consumption of the feeder could be supplied by wind energy. Based on this the necessary rating of the pump/generator has been determed in order to avoid steady state over-voltages in the worst case (low load, high wind). The system is then simulated using SimStore and the installed wind farm capacity is reduced in order to avoid dumping wind energy due to full storage in situations with high grid voltage.

The consumption of the feeder is based on assumption on the load pattern and is taken to be equal to the middle value between low and high load. This equals approx. 12*600 kW installed wind farm capacity.

The wind turbines are assumed to be installed at Cronalaght. The installed capacity is the total capacity at Cronalaght including the existing 5*600kW.

The costs of the different alternatives are calculated and compared. The basic assumption is that the costs the wind turbines and the installation of them are outside the costs included in the assessment. The only costs included are the investment in additional equipment or grid reinforcement and the value of the energy lost. The lost energy is either dumped or it is lost in the pumped storage plant.

The investment in the pumped storage plant at Gweedore is assumed to be between ½ and 2/3 the specific cost of the plant at Lough Altan. The cost of the system at Ballykeeran is taken as the cost of Lough Salt. The pumped storage plants are given a capacity credit of 2/3 of the rating and the cost is equivalent to the cost of installation of a gas turbine, 670 ECU/kW.

The cost of the grid reinforcement is assumed to belong to the interval from 30kECU/km to 40kECU/km since the figure given by ESB is 35kECU/km.

The value of the energy is assumed to be 0.04ECU/kWh. The losses in the grid are neglected. This includes the reduced losses due to grid reinforcement.

The project life time is 20 years and the interest rate is 5% p.a.

Table 6 Total investment of the different alternatives.

		Imin	Imax	Capacity Credit	Itot,min	Itot,max
		kECU	kECU	kECU	KECU	kECU
11*600kW	No storage, No grid reinforcement	0	0	0	0	0
11*600kW	Pumped storage @ Gweedore	2264	3018	2233	30	785
11*600kW	Grid reinforcement (15.7+ 17.6 km)	999	1332	0	999	1332

The investment in pumped storage plants is heavily reduced by the value of the capacity credit. The result is that in the 11*600kW case the pumped storage alternative has the lowest investment, Table 6.

Table 7 Energy losses and value of energy losses for the different alternatives.

		Estor,loss	Edump	Value of loss
		MWh	MWh	KECU
11*600kW	No storage, No grid reinforcement	0	7104	3541
11*600kW	Pumped storage @ Gweedore	1685	77	883
11*600kW	Grid reinforcement (15.7+ 17.6 km)	0	0	0

The grid reinforcement is designed so that it is not necessary to dump any wind energy. The losses are therefore zero in the grid reinforcement cases. The losses in the two other types of case, pumped storage and no storage, no reinforcement, are calculated on the basis of the SimStore simulations, Table 7.

Table 8 Total cost of the different alternatives.

		Tc,min	Tc,max
		kECU	kECU
11*600kW	No storage, No grid reinforcement	3541	3541
11*600kW	Pumped storage @ Gweedore	913	1668
11*600kW	Grid reinforcement (15.7+ 17.6 km)	999	1332

In the case of 11*600kW the cost of grid reinforcement and pumped storage are in the same range. It is necessary to investigate further mainly the assumptions behind the cost estimate of the pumped storage plant in order to find out if this option can compete with grid reinforcement.

The options can also be compared with the installation of a gas turbine delivering the same amount of energy.

The fuel cost is taken as the current world market price (Jan 1999), 101USD/t or 87ECU/t, C_f. The efficiency of the gas turbine is assumed to be 35%, η. The energy content of the fuel is 11.86 kWh/kg, E_s.

The energy production is taken to be the same as the energy delivered to the grid by the 6*600kW wind farm combined with the pumped storage plant.

The investment in the wind farm is assumed to be 1.350kECU/kW including foundation and grid connection.

The production cost of energy can be calculated as

$$\frac{1}{\eta} * \frac{1}{E_s} * C_f = \frac{1}{0.35} * \frac{1}{11.86} * 87 = 0.021 ECU / kWh$$

The total energy delivered to the grid is (from the simulations) 27.453MWh.

An estimate of the levelised production cost (LPC) is in Table 9.

*Table 9 Production cost comparison, 11*600kW case*

Wind Farm		Gas Turbine	
Wind turbine investment	4860 kECU	Investment (Capacity credit)	2233 kECU
Pumped storage investment	3018 kECU	Fuel cost	3918 kECU
Total	7878 kECU	Total	6151 kECU
LPC	0.042 ECU/kWh	LPC	0.033 ECU/kWh

The break even fuel cost can be calculated to 125 ECU/t. This value is 50% higher than the current world market price but the current world market price is extremely low.

The estimates above are very rough, but they indicate the order of magnitude of the production costs involved. There are several aspects that have to be taken into account. These include:
- is it necessary to install dispatchable power plants in the region;
- will the investment in pumped storage plants be outdated by the building of a new 110kV line in the region;
- the calculation is very sensitive to the fuel cost. Will they stay low;
- to which degree is the industrial development limited by the capacity of the grid.

Only detailed considerations by the planning people involved can answer these question. It is outside the scope of this project.

To summarise the case:
The wind resources in County Donegal are very good with average wind speeds of more than 9m/s at 30m agl. There is therefore a large potential for wind power in the region.

The analysis has shown that the grid can only absorb a limited amount of wind power and that a very substantial amount of that is already installed. The existing wind farm at Cronalaght is equipped with a Voltage Control Unit in order to limit the power output from the wind farm in order to avoid over-voltage situations.

There are several sites which are favourable for installation of pumped storage plant of the relevant size. The costs associated with installation of such plants make it reasonable to consider the combination of pumped storage and wind power.

Two main scenarios have been studied. The first scenario includes an increase of the existing wind farm with an additional 6*600kW wind turbines. The different alternatives are then dumping all wind energy necessary for keeping voltage below the upper voltage limit, installation of a suitable pumped storage plant and reinforce the grid. The pumped storage is assumed to be installed very close to the wind farm. The second main scenario includes an additional wind farm of 3*600kW with the same alternatives but the pumped storage plant is installed at another site some distance from the wind farm.

The analysis has showed that for the first scenario is the cost of the combined wind farm/pumped storage plant and the grid reinforcement approximately the same so only a more detailed study will be able to find the least cost option. Also other considerations may have to be included in the analysis like possibilities to increase the industrial development etc.

The least cost option for the second scenario is the grid reinforcement. This option is far cheaper than the alternatives.

Both the combination of wind farm and pumped storage from the first scenario and the grid reinforcement in the second scenario have been compared with conventional generation. Gas turbine generation has been chosen since this most likely will be the type of generation that is displaced. This comparison indicated that with the current fuel prices the least cost option is generation using gas turbines. However, it has to be taking into account that the current fuel prices are very low.

The main result is that with the current fuel prices the generation of energy using gas turbines is the least cost option. However, it is very important that future development in the fuel cost is taken into consideration before decision is made on which option to chose.

An optimised design for a pumped storage plant could reduce the investment cost considerably and increases in the fuel cost are also likely to happen. The generation cost from wind energy in County Donegal is quite low due to the very good wind resource in the region. This combined with the increased certainty of the production cost during the life time of the installation make it worthwhile to consider installation of additional wind power in combination with a pumped storage plant.

One additional factor that has to be taken into consideration is the general development of the region. In this development an improved power supply can play a crucial role.

It is very important that the improvements of the network infrastructure include investigations on both development and timing if the grid reinforcement new capacity (both wind, hydro and conventional) and the load increase.

It is recommended that further investigations are carried out especially including local and utility planners in order to have a more complete picture of the development of the region and the possibilities and requirements for that development.

4.6   Market Analysis

The objectives of the market assessment and identification of project follow-up activities are:
- to establish an impression of the size of the potential market;
- establish contacts with local authorities, power utilities potential investors etc.
- get an impression of the how such systems are perceived by the above mentioned actors;
- identify barriers for the implementation of the technology;
- identify potential demonstration sites and other follow-up activities

The main focus has been on finding potential demonstration sites since the technology is still immature and there is much uncertainty (technical and economical) among decision makers.

It is too early to establish a general overview on the market potential for wind energy and power control concepts in areas with a weak grid infrastructure. One obvious reason is that the power control concept is not yet well demonstrated. Secondly, the economics for the concept cannot clearly be presented due to site specific conditions which have to be taken carefully into consideration.

However, it is of importance to indicate what sort of regions should be further exploited in order to look for demonstration activities in the field. Of even bigger importance is it to look for local actors who are able and willing to support the further process of establishing demonstration activities in the field.

The assessment undertaken as part of this research project has concentrated on the establishment of contacts to market actors on all levels, i.e. power utilities, financial circles, local authorities, regional energy offices etc., to present the concepts in question for such actors, and to motivate such partners to look further into the possibilities of setting up demonstration activities in their own region.

Regions have been selected taking at least three criteria's into consideration, i.e. 1) an interesting wind potential, 2) an interesting small hydro potential (when pump storage is looked at) and 3) a weak grid situation. Preference has been given to areas where local actors already have experiences in establishing renewable energy projects of the nature in question. Such experiences are essential if demonstration activities in the field shall go ahead in the short run.

Potential demonstration activities have been discussed with a high number of local actors in the selected regions. It has been experienced that due to competition concerning economic support for demonstration activities, for example through THERMIE, some local agencies etc. who have been approached, have decided not to continue the collaboration with the working team, even if interesting potential demonstration projects in the field have been identified. This fact, together with the fact that

the existing resource estimates are not made for pump storage purposes, and that a detailed overview of the grid situation in the European regions does not exist, leads to the conclusion that the work undertaken in the framework of the existing JOULE contract as far as market assessment is concerned must be seen as a very first step. Much more work, based on more details on the overall economics and technical reliability for the technology in question, has to be undertaken before any overview of the market potential for the technology can be established.

No work of any systematic nature has so far been done, neither on national nor on European level, to verify the market potential for power control concepts in weak grid areas when looking at renewable energy applications. To be realistic, only a small step forward has been taken on the subject as part of this analysis.

Firstly, the very complex nature of an analysis of this sort can not be undertaken in the framework of the JOULE project. Resources available for such work are far too limited. Secondly, and of even bigger importance, is the fact that key data on the economics for the technologies in question are not yet of a nature that can constitute a sound basis for investors and other decisionsmakers to go for project implementation before very detailed and site specific analyses have been established. Thirdly, the technology is in a very early stage in the sense that for example the control system for the PQ-controller has not yet been developed. As far as batteries are concerned, the research and demonstration are lacking behind in general.

The main objective concerning the investigation made for this project has been to give an overview of potential regions and market actors who have the potential to carry on with the process after the finalization of this project in order to bring the technologies in question into a demonstration phase. At the same time, the goal has been to disseminate the results of the analyses in a way which successfully can lead to further activities in the field throughout Europe.

This being the overall objective and methodology for the work, it can be concluded that there is a big interest for a number of parties throughout Europe to go into more detailed analyses on the possibility of combining wind energy and small hydro in a weak grid context. Market actors have in general been very open minded, and the scope for demonstration activities seems much broader in the context than estimated when the work programme for the project was drafted. Market actors tend more to think in broader terms of 'intelligent storage of energy' than giving power control a narrow focus. In this respect, reverse pumping, sea water pumping and pumping for artificial dams for irrigation have been brought in, together with desalination and other energy consuming activities (like waste water treatment) in areas with a weak grid infrastructure.

There may be a good logic in broadening the scope for the further work (in terms of demonstration) on technologies for power control in a weak grid context. The market assessment has proved the existens of a number of cases where the extended use of renewable energy can take place, probably without any investment in reinforcing the grid, if reliable technical solutions concerning power control are introduced.

In the short run, demonstration activities on wind energy/pumping can be prepared for on the island of Ikaria in Greece, where an artificial dam has been established in the altitude of 700 meters above sea level.

A wind energy/pump storage project can also be prepared for on the Canary islands, even if the local parties prefer not to involve organisations who have participated in the JOULE project.

Also in the Northern Portugal, local parties are preparing for pre-feasibility activities in the field of wind energy/pump storage as a follow-up to this project.

Finally, local parties in Donegal, Ireland, are preparing for follow-up activities in the field of wind energy/pump storage as part of this project.

Other market actors may follow this line. For example have Finnish actors reported back that the concept may be of interest for arctic sites in Lapland in the end of long power lines, and also in the island communities of the Aaland islands.

As far as battery storage for power control is concerned, the market has reacted with considerable scepticism. Any successful big scale utilisation of batteries for power storage on a sound economic basis can not be referred to so far. Furthermore, it has never been demonstrated how batteries will react to big fluctuations (when connected to wind turbines) over a long period of time. It may be so that the life time of batteries in this context is very short under real life conditions. Finally it has been questioned if the multipoled direct drive wind turbine may be a much more logical solution to power control problems in a weak grid context.

Only one market actor has indicated a positive interest in demonstrating the battery concept, i.e. the utility company on the Azores. Since such demonstration should take place as part of an upgrading of existing turbines, which can be done at very low cost, there seems good logic in looking for further support for a demonstration activity there. A demonstration project should not only concentrate on the power control issue, but also go further into the long term behaviour of the batteries themselves.

5 Results and conclusions

A framework for assessing power control systems in both technical and economic terms and for comparison with alternatives like dumping of excess wind energy and grid reinforcement has been established.

As a part of this framework simulation models have been developed. By using these models sizing of the storage unit can be assessed and the impact of the grid in both steady state and dynamically can be estimated. The models are INPark (INETI) for dynamic voltage simulations and SimStore (Risø) for steady state voltage simulation including storage.

The estimated economic performance of power control systems have indicated the technology can compete with grid reinforcement in terms of cost of energy. The estimates did also show that systems using batteries are most relevant for smaller systems and for larger systems is pumped storage the preferred technology (in terms of economy).

A prototype of a 'add-on' power controller has been designed, implemented and tested (ABB: power electronics and its control, Risø: overall control of combined system). The results indicate that such technology can indeed smooth the power output from wind turbines. Unfortunately the full potential of the technology has not been revealed due to limitations of the current controller hardware.

Two case studies have been carried out.

The first study, in Madeira (PT), the main result is that additional wind power capacity can be installed and absorbed in the system without steady state voltage problems, voltage fluctuation problems and excess wind energy problems without installation of power control systems. The island is not suited for pumped storage since the soil is porous. The local utility is not interested in applying batteries. The additional wind power capacity well lower the overall generation cost. This is due to the favourable wind resources of the island.

It is therefore recommended that this additional 1.2MW wind turbine capacity is installed.

The case study in County Donegal showed very favourable conditions for pumped storage and the wind resources are some of the best in Europe. Applying the framework to a weak feeder showed that the cost estimate of a pumped storage system combined with a extensive addition of wind power capacity (adding 6*600kW to 5*600kW) is in the same range as an grid extension. A more detailed design of the pumped storage plant might result in lower cost of that. It is recommended that after a new Development Plan for Co. Donegal a detailed study on a preferred site is carried out including a broad investigation on the overall improvement of the power supply of the region including grid reinforcement at 110kV and 38kV, utilisation of wind and hydro power and forecast of the load.

The market assessment indicated that around Europe there is an interest in especially systems with pumped storage. In order to prove the concept and reduce the risk for possible owners/investors it is necessary to implement demonstration projects.

Further work is suggested in the following areas:

- Demonstration of power control concept based on pumped storage,
- Further development of 'add-on' and 'integrated' concepts especially on the controls,
- Further development of the models needed as part of the developed framework.

6   Exploitation plans and anticipated benefits

The two main issues involved are demonstration of the concepts and further development of the add-on and integrated concepts hardware.

The costs involved in the demonstration process are so high that financial support is necessary. The major sources here will be EU programmes with support from national programmes.

The further development of the hardware will also require external funding. National programmes will be more important here but still EU will be a relevant source for financial support.

The knowledge gained through the project by the participants will be exploited by each of the participants. It will form the basis for further research work by the research institutes involved (Risø, INETI and also ABB) and will be used by the other participants in order to promote further integration of wind energy in areas with a weak grid. Technology that can ease the integration of wind energy can play an crucial role in the future when large amounts of wind energy has to be integrated in the power system.

The anticipated benefits include the possibility to economically utilise the vast wind resources in areas with a weak grid by avoiding costly grid reinforcement. The project has shown that power control systems can be the least cost option (of power control, grid reinforcement, dumping of wind energy). It can also benefit the region where it is applied by improving the electricity supply making it possible to further develop the region.