POWER CONVERTERS FOR FLYWHEEL ENERGY STORAGE SYSTEMS

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Contract JOR3-CT95-0070

Publishable Final Report
(non-confidential)

Period 1st January 1996 to 31st October 1998

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

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1. Abstract

The project aimed to implement and test flywheel energy storage systems for smoothing power fluctuations from wind turbines and other renewable energy systems. A small-scale energy storage system has other potential applications in electrical power systems, such as the support of weak grids, regenerative power-saving systems, and uninterruptible power supplies.

The requirements for flywheel energy storage systems (FESS) to be used with wind energy systems, in both mains grid-connected, and autonomous (diesel genset) applications, were defined by Rutherford Appleton Laboratory (RAL) and University of Leicester. It was anticipated that the requirements could be met by conventional steel flywheels operating at speeds up to 6000 rev/min.

Two FESS configurations were considered, using a mechanical Continuously Variable Transmission (CVT) drive, and a power electronic (PE) drive, which were developed and factory tested by their respective manufacturers P.I.V. Antrieb Werner Reimers GmbH & Co. KG, and Cegelec Industrial Controls. These drives were integrated with electrical machines and steel flywheels on the RAL Wind Test Site, resulting in two prototype FESS with characteristics suitable for the target applications. Controllers for the CVT drive and PE drive were developed by RAL and University of Leicester respectively, and the two FESS were tested for specified performance under test conditions, and in the wind-power smoothing application. The overall performance of both drives has been shown to be excellent, with fast response times being achieved; and the capability of the FESS and controllers to smooth wind power fluctuations, leaving only relatively low amplitude power fluctuations at frequencies above several Hertz, was successfully demonstrated in both mains grid-connected, and autonomous (diesel genset) applications.

Finally, an evaluation of the application test results of the two systems enabled a comparison to be made of their relative merits. This revealed that the system utilising a power electronic drive is suitable for power smoothing and reactive power compensation in all types of power system, and particularly in grid-connected systems with rated powers in the range 10 kW to 2 MW. The system utilising a mechanical CVT is applicable to small autonomous (diesel-genset) power systems, with rated powers up to 300 kW, where the synchronous machine together with the high effective inertia provided by the CVT and flywheel offers reinforcement to power systems which are weak in terms of frequency and voltage. In the light of operational results, recommendations were made for possible improvements to both systems, including configuration and controller design.

A total of seven technical papers have been written and presented by the investigators at six national and international conferences and colloquia. The experimental systems on the RAL Wind Test Site have been viewed by visitors during Open Days. Both industrial collaborators have demonstrated improved drives resulting from the project developments.

2. Partnership

The project co-ordinator, Rutherford Appleton Laboratory (RAL), is a research institution which has been active in the field of renewable energy research for a period of 18 years, including autonomous wind-diesel power systems, and the application of flywheel energy storage in power systems. RAL operates a Wind Test Site which includes several wind turbines, flywheel energy storage systems, and a photovoltaic / wind stand-alone system.

P.I.V. Antrieb Werner Reimers GmbH & Co. KG manufactures a range of transmissions, including infinitely variable mechanical variators, fixed speed gearboxes and gear-motors, worm gears, special gears, and couplings. P.I.V. is an established manufacturer of CVTs, with design, manufacture, and test capability with quality control approved to ISO9001.

CEGELEC and parent company Alstom is a large international company with a world wide presence in the field of electronic variable speed drives and industrial control. Cegelec is an established power electronic drive manufacturer, with design and manufacturing quality control approved to ISO9001.

Leicester University Engineering Department has a very successful programme of collaboration with industry, other universities and government departments. Current research interests include solar, wind and hydro power, energy storage and hybrid vehicles, and improvements in energy conversion efficiency using power electronics.

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3. Objectives

3.1 Introduction

The project set out to address the requirement for short term energy storage with rapid charge/discharge cycling, typical of operation with renewable energy systems such as wind and wave. Flywheel kinetic energy storage is a suitable technology for use as a short term energy buffer, capable of high power transfer with continuous charge / discharge cycling, as required for power smoothing in renewable energy systems, as well as in many industrial and transportation applications. The overall project objective was to develop complete FESS to a level where they could be incorporated in future demonstration renewable energy systems. It was recognised that the most important technologies requiring development were the PE and CVT drives for incorporation in the two pilot FESS configurations, together with associated sensor and controller developments. These could then be integrated and tested with existing conventional steel flywheels.

3.1.1 CVT drive development

The objective was to develop a 30 kW mechanical Continuously Variable Transmission (CVT), together with sensors, ratio and power controllers, capable of fast response when operating in torque and speed control modes. This power converter was to be integrated in an existing synchronous motor / generator and flywheel system.

The standard mechanical CVT manufactured by P.I.V. is a robust and highly reliable drive which has been applied extensively in marine applications to provide a constant frequency electrical supply from the main engine, which runs at variable speeds according to the propulsion demand. The CVT transmits power via a metal chain running between pairs of conical disks on the input and output shafts. One disk of each pair can be moved axially by hydraulic pressure, and a speed change is achieved by moving the disks in opposite axial directions, causing the chain to run on different radii.

The following developments were required to produce a drive suitable for application in a flywheel energy storage system :

• a hydraulic clamping system to enable highly dynamic bi-directional torque transmission, without belt slippage.
• control of hydraulic pressure in the cylinders to reduce load-dependency.
• sensors for measurement of input and output speeds.
• an electronic closed loop control system for precise speed / ratio control, independent of load.
• a torque sensor for closed-loop torque control.
• a fail-safe hydraulic pump design for efficient operation.

3.1.2 Power electronic drive development

The objective was to develop a bi-directional 45 kW power electronic variable speed drive and controller, capable of fast active and reactive power control, and suitable for integration together with an induction motor / generator and flywheel system.

The Alspa GD4000 range of variable speed drives manufactured by CEGELEC has important features which make it suitable for use in a flywheel drive :

• the machine inverter with flux-vector control provides accurate torque control of the standard induction machine in motor and regenerative operation.

• the bi-directional sinusoidal current mains inverter ensures harmonic free operation, and allows control of the power factor (including unity and leading). The design replaces traditional thyristor rectifier technology with a voltage source inverter based on fast transistor IGBT switches to achieve sinusoidal current in the power network. This is important to satisfy legislated limits on harmonic emission, and is particularly relevant when the drive is operated on a weak grid, such as an autonomous system or at the end of a long feeder.

3.2 Controller development

Development of controllers for both FESS would be required in order to provide active power smoothing and reactive power compensation in renewable energy systems, as well as frequency control of fully autonomous systems. The external interfaces to a complete FESS suitable for inclusion as a component in a power system, would normally include active and reactive power control signals, and a partition would be defined to allow development of controllers for the acquisition (external to FESS), and utilisation (internal to FESS) of these signals.

3.3 Application testing

The objective was to test the two flywheel energy storage systems in both mains grid-connected, and autonomous diesel genset connected configurations, in conjunction with a stall-regulated Windharvester wind turbine with induction generator. The performance of the two systems would be assessed in the target applications, and also in relation to applications for drives requiring torque and speed control.

4. Technical description

4.1 Energy storage in conventional flywheels

Flywheels offer virtually unlimited fast charge and fast discharge cycles at high efficiency, and with minimum maintenance requirements, compared with the limited lifetime and lower efficiency of electrochemical batteries.

The operating principle of a flywheel energy storage system (FESS) is that electrical energy is converted to kinetic energy and stored in the flywheel, and the kinetic energy can be converted back to electrical energy when required later. The flywheel rotor design specification is fundamental to the system; if the flywheel inertia is doubled, the energy it stores at a given speed of rotation is doubled, and if the flywheel speed is doubled, the amount of stored energy is quadrupled. The project was concerned with the development of drives and controllers for conventional steel flywheels, rotating at speeds up to 6000 rev/min, and primarily targeted at renewable energy applications such as wind and wave. Such applications are stationary and do not require a high energy density (the maximum specific energy of such flywheel rotors is only of the order of 5 Wh/kg). The two flywheels at RAL have maximum stored energy of 8.2 MJ (2.3 kWh) at 5000 rev/min, used with the PE drive; and 4.8 MJ (1.3 kWh) at 4000 rev/min, used with the CVT drive. Such conventional flywheels operating at speeds up to 6000 rev/min, together with suitable power converters (drives), electrical motor/generators, and controllers, offer a number of benefits :

(i) the flywheel rotor can be constructed from low cost steel disks, and may be manufactured and balanced by conventional techniques.

(ii) the rotor bearings are standard and commercially available, although achieving speeds of 6000 rev/min requires the use of precision high speed bearings.

(iii) the storage capacity can be increased by adding additional rotor modules (effectively increasing the mass and inertia), giving the potential for high capacity systems.

The major drawback of such systems is that the standing losses, which are mainly due to the use of conventional electrical machines operating in free air, are much higher than electrochemical batteries, making them suitable for short term energy storage only.

4.2 Outline requirements for an energy storage system

a) rated power = wind turbine generator rated power
b) storage time (storage capacity / rated power) :

- 30 to 300 s (in autonomous systems; depending on acceptable on-off cycling rate of the diesel genset)
- 10 s (in grid connected systems; to prevent voltage flicker)

c) active power control :

- response time < 0.1s to 90%, with stable response

d) reactive power control / voltage regulation
e) frequency control :

- maximum 5 % (autonomous system with diesel genset stopped)
- able to follow grid frequency, but prevent islanding (grid connected system)

f) losses directly affect the system economics, and must be as low as possible :

- standing losses < 5 % of rated power
- charge (& discharge) efficiency > 95 %.

g) charge / discharge cycles > 10^6

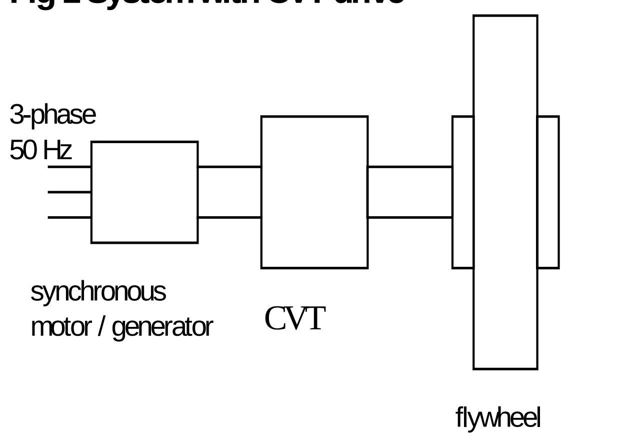
4.3 Flywheel energy storage system configurations

The two flywheel energy storage systems were integrated and installed on the RAL Wind Test Site. The flywheel in each system is operated asynchronously, allowing it to be operated up to its maximum design speed, and thus utilising its maximum storage capacity. The two systems use different technologies to achieve their objectives :

<u>(i) a system with 30 kW mechanical continuously variable transmission (CVT)</u>
The storage system consists of a flywheel, a CVT, and a synchronous machine, which is connected to the electrical supply. The drive and associated controller is capable of speed and power control.

Flywheel inertia	: 55 kg m^2
Flywheel max. speed	: 4000 rev/min
Max. storage capacity	: 4.8 MJ (1.33 kWh)
Rated power	: 30 kW
Storage time	: 159 s

Fig 1 System with CVT drive



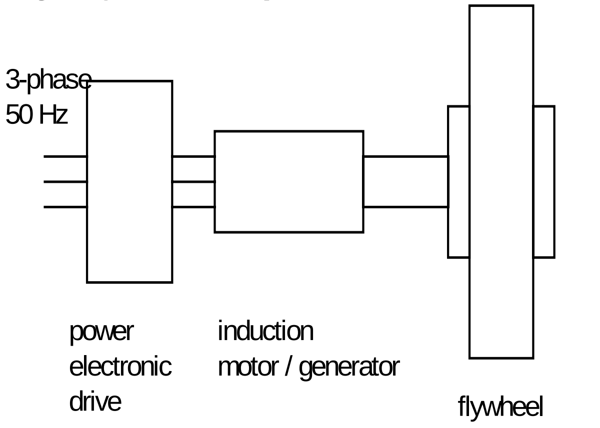
The main advantages of this system when connected to autonomous systems are that the CVT directly couples the flywheel inertia onto the electrical network; the synchronous machine can provide reactive power to the network; and the system can be easily retrofitted to an existing wind-diesel power system. The mechanical CVT drive is based on P.I.V.'s system RHVF147. This drive is inherently speed (ratio) controlled, however controlling power flows requires torque control. The most important development on the new drive is a torque sensor, which provides an immediate feedback between torque and clamping force on the input and output disks, and also enables closed loop torque control directly on the CVT.

(ii) a system with 45 kW power electronic variable speed drive

The storage system consists of a flywheel, directly connected to an induction machine, and a power electronic drive, which is connected to the electrical supply.

Flywheel inertia	: 60 kg m^2
Flywheel max.speed	: 5000 rev/min
Max.storage capacity	: 8.2 MJ (2.28 kWh)
Rated power	: 45 kW
Storage time	: 182 s

Fig 2 System with power electronic drive



The development of a modular PE drive with adequate control of active and reactive power would allow the exploitation of this FESS concept in grid-connected applications over a range of rated powers. The electronic variable speed a.c. drive uses at its core a standard industrial drive product - Alspa GD4000. This drive was selected specifically for its 4-Quadrant characteristic that allows full control of the flywheel power flow during charging and discharging periods. The standard industrial drive selected for this project is revolutionary compared to many other offerings in the market place in that it provides a sinusoidal input rectifier to achieve both unity or controllable power factor and low harmonics in the supply network. This is highly desirable in a weak network situation, typical of many applications where flywheel energy storage systems combined with wind turbines may be required.

5. Results and conclusions

5.1 Summary

Two drives, a CVT drive and a PE drive, have been successfully developed, integrated into two prototype flywheel energy storage systems, and tested in a range of wind power smoothing applications. The overall performance of both drives has been shown to be excellent, with fast response times being achieved; and the capability of the FESS and controllers to smooth wind power fluctuations, leaving only relatively low amplitude high frequencies, was successfully demonstrated. However, the performance of both FESS still falls somewhat short of what is ideally required in terms of response time and stability, although it is fair to say that the original objectives were very ambitious and testing.

The techniques adopted for power smoothing, viz., measurement of the wind turbine power, high-pass filtering of the power signal to generate a power demand signal, and parallel connection of the energy store; all demand wide bandwidth and low phase shifts. In situations where there is no control over the generated power, this mode of operation is mandatory. The results demonstrate the feasibility of using a FESS to smooth power fluctuations at frequencies up to a few Hertz. In order to achieve a wider bandwidth, additional techniques should also be considered, such as controlling the generated power by variable speed operation of the wind turbine.

5.2 Operational results of FESS with CVT drive

When operated on a mains grid (fixed frequency) the FESS smoothed wind power fluctuations at frequencies up to 0.5Hz, which includes most of the fluctuations. Low frequency fluctuations with periods up to 200s were effectively smoothed by the FESS, while fully utilising a storage capacity of only 10s x rated power. The prototype FESS actually has a much longer storage time of 159s, and could smooth power fluctuations up to much longer periods when operated with a suitable wind power signal filter. The FESS synchronous machine, fitted with an Automatic Voltage Regulator (AVR) and Power Factor Controller (PFC) provided the wind turbine reactive power requirements, leaving the mains grid to supply only low amplitude fluctuations at frequencies above 0.5Hz.

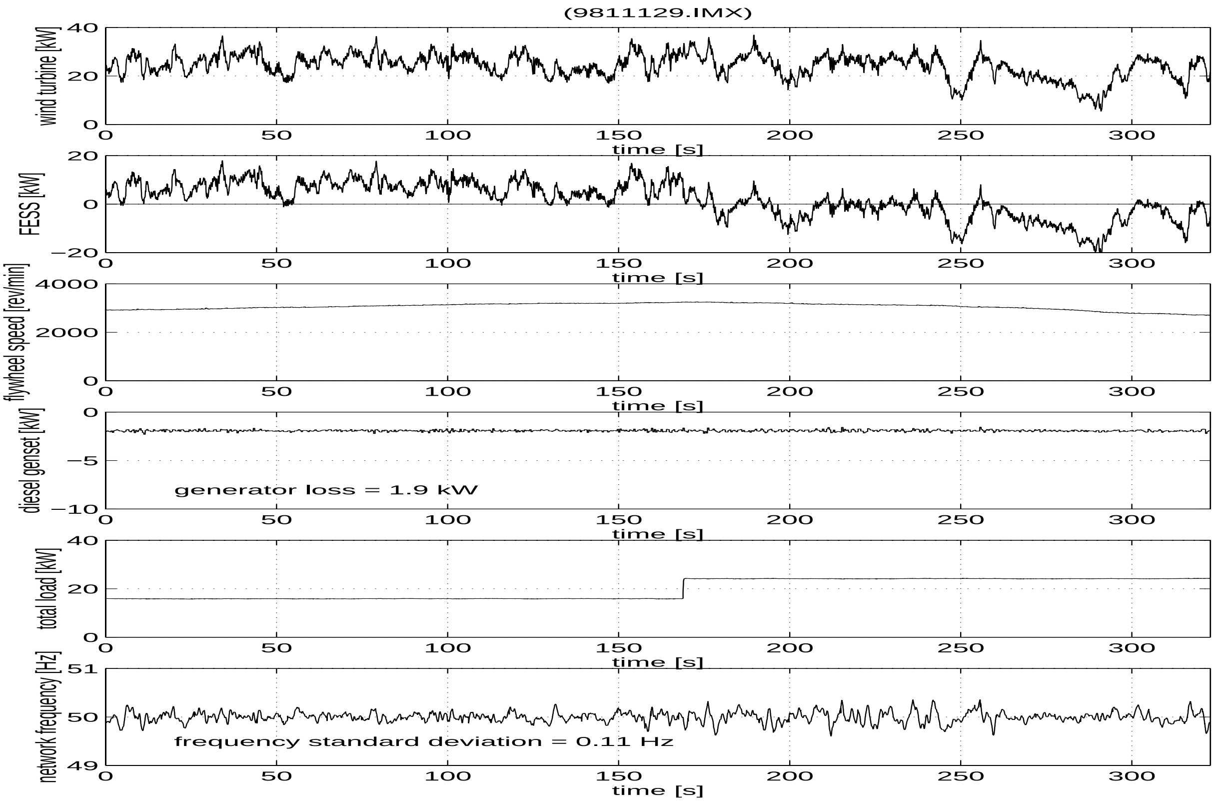


Fig. 3. Power smoothing with independent operation of the wind turbine

The FESS with CVT is an attractive choice for operation in an autonomous power system, where a diesel generating set (genset) is used as the prime mover. The system is capable of regulating voltage and frequency with the diesel genset disconnected, and therefore may be easily retrofitted to a system with an existing diesel genset, without incorporating an electromagnetic clutch. The new torque sensor enables the CVT to maintain ratio to a close tolerance even with torque fluctuations, and this means that the flywheel inertia is more directly reflected onto the electrical network without external control action. This allows the FESS to regulate frequency to a close tolerance when smoothing wind power independent of the diesel genset, for example frequency regulation within a standard deviation of 0.1Hz was achieved with wind power fluctuations in the range 5 - 35kW, as shown in Figure 3

When operating in parallel with a diesel genset, a response time to step power demands of 0.25s was achieved, and power fluctuations at frequencies up to 4Hz were absorbed. This makes it feasible to operate the diesel genset at a fairly steady level without dumping power, resulting in significant fuel savings. However, some instability at frequencies around 0.5Hz was noted. It has been noted that small wind-diesel systems have complex interactions between the components, and it may be difficult to completely eliminate the resulting power flows. A further feature of the new ‘stiff’ CVT is the capability of the FESS to assist the diesel genset supply sudden load transients, which may avoid the need to oversize the diesel genset in applications where there are severe load transients, or where improved frequency regulation is required.

5.3 Operational results of FESS with Power Electronic drive

The PE drive is particularly suitable for power smoothing in the mains grid connection application, where the fast response enables it to smooth power fluctuations at frequencies up to several Hertz. It is also capable of providing the reactive power required by the wind turbine, and therefore will significantly improve the voltage regulation at the point of coupling on a weak grid. A typical time series of 10 minutes is shown in Figure 4, where the dashed trace represents the wind turbine

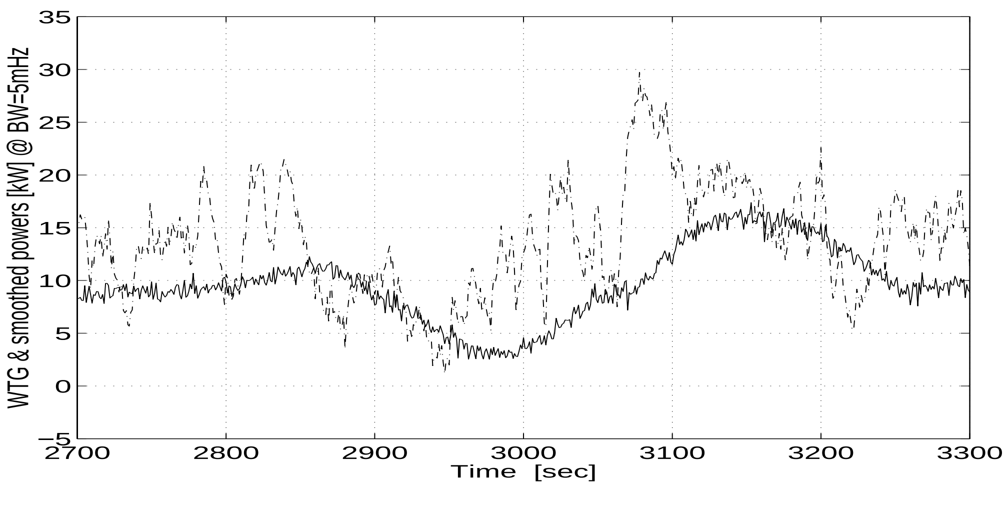


Fig.4. Power smoothing with grid-connected wind turbine

output power and the continuous trace the power supplied to the grid. It is obvious that the presence of the flywheel energy storage system results in a considerable degree of power smoothing. While the wind power exhibits power fluctuations from almost zero up to 30 kW over a wide range of time scales, the variation in power delivered to the mains grid is much slower and more restricted.

The effectiveness of the energy buffer in the system can be assessed more easily by spectral analysis of the time series. Figure 5 shows the spectra of the wind power (dashed) and grid power (full) over the frequency range up to 1 Hz, where the FESS absorbs most fluctuations with period in the range from 1 second to 2 minutes.

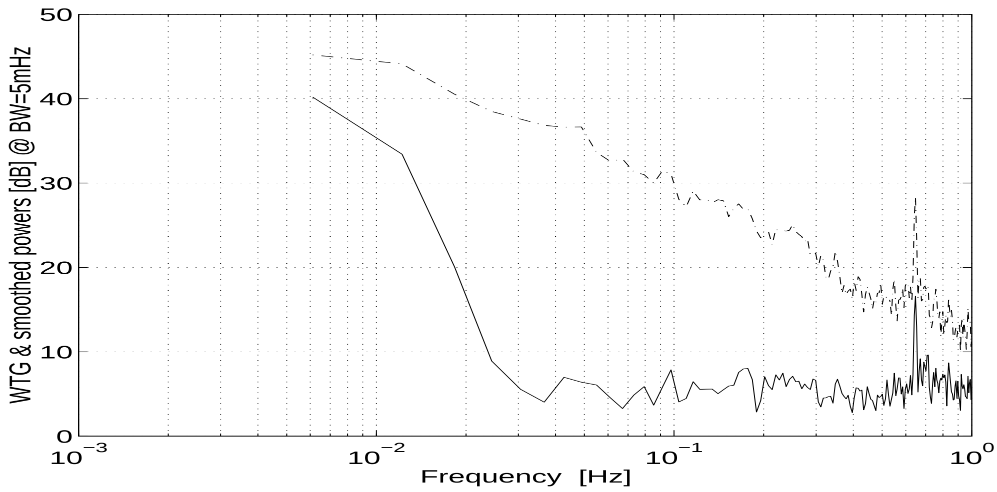


Fig. 5. Spectra of wind power and grid power

Observations showed that the reactive power of the grid remained very close to zero during these experiments, indicating excellent reactive power compensation.

As a result of the considerable degree of power smoothing, in particular in the frequency range up to a few Hz, combined with reactive power compensation, the voltage disturbances ('voltage flicker') at the point of common coupling with the grid will be greatly reduced.

6. Exploitation plans and anticipated benefits

6.1 Exploitation plans

The industrial partners are committed to developing the technology of their respective drives. This project has demonstrated the feasibility of flywheel energy storage systems in both grid-connected and autonomous power systems, as well as the relative merits of the two FESS configurations. However, exploitation of the potential market for flywheel energy storage systems depends on a market response. In the case of wind-diesel systems the technical and economic benefits of energy storage are clear, however implementation requires additional capital investment, and exploitation is expected to be sensitive to the cost of diesel fuel, which is currently very low.

P.I.V. have a well developed network of Sales Offices, European subsidiaries, and worldwide representatives. The availability of the new torque controlled drive is useful not only in flywheel energy storage systems, but could open up markets for sophisticated drives in transport and industrial applications. In transportation, a recent innovation at P.I.V. is the development of a drive for air-conditioning plant, and other equipment in buses and small trains, resulting in overall energy savings. In industry, precise torque control has important application to production processes involving rolling and coiling, such as the paper and textile industries. An important aspect of these applications is energy savings in general, and commitment by P.I.V. to improving the conversion efficiency of the CVT drive should ensure successful applications.

CEGELEC and parent company Alstom have a world wide presence, which will give global opportunities for products arising from this development. It is also proposed that the hardware and software developments in this project will find application in a wide range of variable speed drive markets, in addition to energy storage systems. The use of fast torque regulation in applications such as metal processing, materials handling, and lifting systems are immediate opportunities for diversification.

The results of the individual drive developments, and the results of application testing have already been published in seven technical papers, presented at Conferences such as EuroSun'96, Universities Power Engineering Conference (UPEC'97), International Conference on Electrical Energy Storage Systems Applications and Technologies (EESAT'98), British Wind Energy Association Annual Conference (BWEA20), IEE Power Electronics and Variable Speed Drives Conference (PEVD'98); and has been discussed at an IEE Colloquium on Power Electronics for Renewable Energy, and at a meeting of the Power Engineering Chapter of the IEEE in West Australia.

The techniques for torque and speed control developed in the project have been applied by the respective manufacturers to improve the performance of existing products, with possible new business opportunities. Besides renewable energy systems, other stationary applications for flywheel energy storage systems include :

- Support of weak grids, including network reinforcement at the end of long feeders.
- Uninterruptible power supplies, providing power to ride-through a temporary grid supply interruption, or until a back-up diesel generating set can be started and brought on-line.
- Energy storage schemes for transportation, such as trackside support, enabling energy saving by regeneration, and providing additional power for train acceleration.
- Replacement for electrochemical batteries subjected to frequent cycling.
- Short term rated, high energy power sources in situations where existing supply networks cannot support the demand - e.g. high energy physics.

6.2 Anticipated benefits

The environmental attractiveness of renewable energy as a replacement for fossil fuels is well established. However, renewable energy sources are generally intermittent, and in autonomous systems solutions are required to match the available power to the demand power. In grid integrated systems, the power fluctuations are known to give rise to grid integration problems particularly where the grid is weak, and despite the availability of wind resource, remote sites may not be considered. The availability of short term energy storage using flywheels offers an economic solution to the local supply quality problem.

The project has developed short term energy storage systems which would allow exploitation of the potential wind resource in situations which are currently regarded as uneconomic. These include :

(i) remote communities without a grid connection, where electrical power is supplied by diesel generating sets, at costs of up to ten times that of large generating stations. A FESS enables substantial fuel savings to be made when integrated together with wind energy converters in the power system.

(ii) remote renewable energy systems, grid connected via a weak feeder. The inclusion of a short term energy storage system could offer an economic solution to supply quality problems, compared with the alternative of strengthening the grid connection by upgrading the feeder, where the cost may be prohibitive.

In addition, the proposed developments also have important applications in many areas of transport and industry, where variable speed drive technology with precise speed and torque control is required, and where the conversion efficiency is crucial to achieving energy savings.

7. Illustration of potential applications