

**EUROPEAN WAVE ENERGY PILOT PLANT ON
THE ISLAND OF PICO, AZORES, PORTUGAL.
PHASE TWO: EQUIPMENT**

Contract JOR3-CT95-0012

PUBLISHABLE REPORT

1st January 1996 to 31st October 1998

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SUMMARY

The project concerns Phase Two of the design, construction and commissioning of a power plant of oscillating water column (OWC) type to be installed at Porto Cachorro, on the northern shoreline of the island of Pico, Azores, Portugal. Phase One, which was the object of contract JOU2-CT93-0314, concerned the plant basic studies, and the design and construction of the air chamber structure. The present project — Phase Two — concerns (i) the remaining civil engineering work, (ii) the design, construction and erection of the mechanical, electrical, control and monitoring equipment, and (iii) the commissioning and start up.

The partners include three universities, one government laboratory and four companies, two of which are utilities. The countries involved are Portugal, United Kingdom and Ireland.

The main objective of the project (phases One and Two) is to demonstrate the technical feasibility of OWC wave power plants by building one at a commercial scale. In addition, the plant was designed to provide a facility for testing power take-off equipment, namely air turbines, generators, control equipment and valves.

The plant consists of a concrete structure standing on the rocky sea bottom, spanning a small gully where natural concentration of wave energy occurs. The oscillating water column has a $12 \times 12 \text{m}^2$ square cross-section. The plant's power equipment is basically a horizontal-axis Wells turbo-generator set. Room has been left to install a second turbo-generator set for testing purposes. The plant is equipped with a relief valve whose purpose is to remove (positive and negative) pressure peaks in the air chamber and in this way avoid aerodynamic losses in the turbine due to rotor blade stalling.

The basic design of the plant, initiated in Phase One, was finalized. Results of the simulation of the power chain conversion (from wave to wire) were used to establish the specifications for the turbine and for the relief valve. A design value of

120 Pa m⁻³s was adopted for the turbine damping coefficient, and 560 kW was adopted as turbine shaft (maximum instantaneous) power output (assuming a turbine maximum efficiency of 80%). An effective cross-sectional area of 0.8 m² was adopted as an adequate design value for the relief valve.

The turbine, generator and the power electronics unit are located in a 10×12m² turbine room behind the air chamber. Most of the remaining equipment (namely electrical, control and monitoring) is located in two rooms under the turbine room.

A major task of the civil contractor was the removal of boulders from the sea bed in front of the plant.

Some damage to the front wall of the structure was detected in summer 1997. Its most likely cause was defective underwater concreting in 1996 (as part of Phase One). Repair work was carried out in summer 1998.

The civil work, which included the construction of the equipment rooms and the roof of the chamber structure, was completed in August 1998.

The aerodynamic design of the Wells turbine was carried out in 1996. The turbine, ducts and two air valves were supplied by Applied Research and Technology Ltd (ART, Inverness, Scotland) in 1997.

The use of a variable speed electrical generator (750 to 1500 rpm) is one of the most important and innovative features of the plant. The development of the non-conventional electrical equipment (especially the power electronics and the control equipment) was a major task of the project. Practically the whole electrical equipment (conventional as well as non-conventional) was supplied by EFACEC Engenharia SA (Portugal).

The plant equipment was erected in summer 1998. An accident, due to flooding by sea water, occurred on 5th September 1998 when some of the conventional electrical equipment was being installed in the lower room of the plant. The damaged equipment (including the 630 kVA transformer and the general AC board) was later returned to factory for repair or replacement. This prevented the plant from becoming operational before the end of October 1998. The repaired equipment is expected to be re-erected in spring 1999. The plant is planned to be fully operational in summer 1999.

1. INTRODUCTION. OBJECTIVES OF THE PROJECT

The project concerns Phase Two of the design, construction and commissioning of a power plant of oscillating water column (OWC) type to be installed at Porto Cachorro, on the northern shoreline of the island of Pico, Azores, Portugal. Phase One, which was the object of contract JOU2-CT93-0314, concerned the plant basic studies, and the design and construction of the air chamber structure. The present project — Phase Two — concerns (i) the remaining civil engineering work, (ii) the design, construction and erection of the mechanical, electrical, control and monitoring equipment, and (iii) the commissioning and start up.

List of partners:

- **IST** – Instituto Superior Técnico, Portugal (Coordinator), university
- **EDA** – Empresa de Electricidade dos Açores EP, Portugal (Contractor), utility
- **EDP** – Electricidade de Portugal SA, Portugal (Contractor), utility
- **QUB** - Queen’s University of Belfast, United Kingdom (Contractor), university
- **UCC** – University College Cork, Ireland (Associate Contractor), university
- **INETI** – Instituto Nacional de Investigação e Tecnologia Industrial, Portugal (Contractor), research institute
- **EFACEC-SE** - EFACEC Sistemas de Electrónica SA, Portugal (Contractor), industrial company
- **Profabril** – Profabril Centro de Projectos SA, Portugal (Sub-contractor), engineering company

The main objectives of the project are as follows:

- (a) To demonstrate the technical feasibility of OWC wave power plants by building one at a commercial scale.
- (b) To provide a facility for testing power take-off equipment, namely air turbines, generators, control equipment and valves. The OWC structure can provide a testing bed for that purpose.
- (c) To provide the means for assessing and validating the overall design methodology (structure geometry, specification of the equipment), the structural design of the chamber, the design and adequacy of the various elements of equipment, and for assessing the methodology for predicting the energy production. This can be achieved from information and data obtained when operating the power plant:
 - measured wave forces (namely impact forces) upon the structure; structure resistance to wave forces and survival under extreme wave conditions;
 - overall performance of the plant; efficiency of the various elements of the power chain (hydrodynamic efficiency, turbine aerodynamic efficiency, generator efficiency); by-pass valve performance; control strategies and procedures;

- reliability and resistance to corrosion and erosion of the mechanical and electrical equipment; maintenance requirements;
 - assessment and validation of the mathematical models and experimental model test methods used in the simulation of OWC performance;
 - interaction between the pilot plant and the electrical grid of the island;
- (d) To assess the economical feasibility of OWC power plants, namely in a small isolated electrical grid, by analysis of costs, including benefits from serial construction, and comparison with other technologies.
- (e) To take advantage of the experience gained with the design, construction and operation of a shore-line device for later use in the development of a second generation of devices to be deployed near shore in deeper water.

2. BASIC DESIGN

The performance of the power plant was simulated numerically by splitting the energy conversion chain into two parts modelled separately: (I) wave into pneumatic energy conversion; (II) pneumatic into electrical energy conversion. Model I is based on linear water wave theory and uses as input data the results from model tests carried out in irregular wave basin at the National Civil Engineering Laboratory, Lisbon (scale 1:35) and at University College Cork (scale 1:25) (these model tests were carried within the framework of Phase One, contract JOU2-CT93-0314). Model II simulates the energy conversion in the Wells turbine and the electrical generator, and includes the effect of a controlled relief valve (by-pass valve). The aerodynamic performance of the Wells turbine was based on experimental data from turbine model testing (available from previous laboratory work carried out in Lisbon). Realistic mechanical losses were assumed for the turbine, as well as mechanical and electrical losses for the generator. The capability to control the rotational speed (to match the wave power level) was duly modelled. The local wave climate was simulated by 44 records from wave measurements at the construction site in the Azores, together with their frequency of occurrence. In order to optimize the turbine specifications, simulations were carried out with different combinations of the values of turbine rated power and turbine damping coefficient. Based on these results, the decision was made to adopt, as design values for the Wells turbine, $K = 120 \text{ Pa m}^{-3} \text{ s}$ for the damping coefficient, and 700 kW for the turbine rated power (pneumatic instantaneous power at maximum rotational speed), or about 560 kW for turbine shaft (maximum instantaneous) power output (assuming a turbine efficiency of 80%).

The function of the relief valve is to remove pressure peaks in the chamber and to prevent the overpressure (or underpressure) of air from exceeding the critical value (depending on the turbine instantaneous rotational speed) above which aerodynamic stalling occurs. Blade stalling in Wells turbines is known to result in severe drop in torque and power output. A study was carried out to assess the benefits that could possibly result from the use of such a valve, and to determine a suitable size for the valve. This study consisted in the detailed theoretical analysis of plant performance,

and was done along the same lines as outlined above, with some important differences: (i) theoretically obtained hydrodynamic (radiation) coefficients were used (rather than coefficients computed from model test results in wave tank); (ii) the hydrodynamic-aerodynamic performance of the plant was theoretically analysed in the time domain; (iii) in the analysis, account was taken of valve cross-sectional area at fully-open valve position. An additional, similar study was also carried out, in which the hydrodynamic (radiation) coefficient was computed from model test results in wave tank. Results were obtained for the annual produced energy by using valves of different sizes. It was found that: (i) a substantial increase in produced energy can be achieved by using a properly controlled by-pass valve; (ii) this depends on valve size. A design value $A = 0.8 \text{ m}^2$ was adopted for the valve effective cross-sectional area, defined as $A = |w_v| (2r|\Delta p|)^{-1}$, where w_v is mass flow rate through the valve, Δp is pressure difference and r is air density.

3. CIVIL CONSTRUCTION

3.1. CIVIL AND STRUCTURAL DETAIL DESIGN

Phase Two included the design and construction of houses where the mechanical, electrical and control equipment was to be installed. In a first conception, the turbo-generator set and some of the electrical equipment (namely the Kramer link and other power electronics) were housed in a turbine room, located on top of the chamber. Most of the conventional electrical equipment (the main transformer, switch-boards, counters, etc.), the control equipment and the data acquisition system were kept in a house to be built on land (level about +8 m) adjacent to the eastern side wall of the chamber. The detail design was developed accordingly and was included in the tender documents for the civil construction which led to the contract signed with contractor Marques Ltd. This conception had to be abandoned due to objections concerning visual impact which were later raised by the Directorate of the Environment of the (Azores) local government. An alternative conception was then developed which was approved by the environment authorities. The electrical room and the control rooms were to be built as part of the chamber structure, behind the rear wall of the chamber and under the turbine room. The dimensions are approximately 7m×5m for the electrical room and 5m×5m for the control room. These rooms can be reached from the turbine room through a staircase.

The heavy equipment can be lowered into (or raised from) the turbine room by a crane through a large opening (5m×3m) on the room's roof. The larger pieces of electrical equipment can be lowered by a monorail winch from the turbine room into the electrical room through an opening on the plate separating the two rooms.

The interior of the chamber, especially the movement of the water free-surface, can be seen from the control room through two portholes, protected by strong bronze covers.

The detail design of the equipment rooms was developed.

3.2. CIVIL WORK AND CONSTRUCTION

The civil construction in Phase Two was carried out by the same contractor as in Phase One: Marques Ltd, with headquarters at Ponta Delgada, on the island of São Miguel, Azores. The civil contractor resumed work in April 1997 by rebuilding the access way which had been damaged during the winter. The Portuguese Meteorological Institute, in Lisbon) kept sending daily by fax to the contractor the forecast for the wave conditions in the near field (deep water). It consisted of a four-day prediction of wave conditions (namely significant height H_s , maximum height H_{max} , and wave direction). Together with the forecast, Instituto de Meteorologia also supplied a hindcast for the same site.

3.2.1. REMOVAL OF BOULDERS FROM THE SEA BED

As part of Phase One work, the civil contractor had erected, in 1996, a temporary cofferdam, made up of large pieces of rock (between one and ten tons each), spanning the entrance to the gully, in order to shelter the construction work from direct wave action. In 1996, the cofferdam was more or less severely damaged by wave action several times. Each time the cofferdam was repaired or rebuilt, the contractor brought more rock from the land. As a consequence of this process, a large amount of rock (estimated to be several thousand cubic metres) was scattered and covered an area of the sea bed extending as far as 50 to 70 m in front of the plant. By the end of November 1996, it was estimated that the scattered boulders formed a layer several metres thick which in some places in front of the plant reduced the water depth to about 2 m. It was obvious that the reduction in water depth would substantially reduce the amount of wave energy flux reaching the plant. Therefore, the contractor was reminded that, according to the terms of the civil contract, they would have to remove all the materials brought to the construction site, including namely the ones they used to build the temporary cofferdam. Two types of equipment were discussed for the removal of the scattered boulders: (i) a floating crane and (ii) a land-based crane. The use of a floating crane was considered too risky, due to the narrowness of the area and the exposition to (frequently strong) wave action. So it was decided to employ the mobile crane which had been in use since the beginning of the work at the site. In order to allow the crane to be positioned as far north and as close to the water as possible (and increase its reach), the contractor constructed, in June, a new platform, extending along the existing cliff.

Inspections carried out by divers in June 1997 revealed that a large part of, possibly most, boulders had already been dragged away to deeper areas by the waves during the winter. It was also observed that what remained was in a more compact condition. This, and the fact that the remaining boulders lay further away from the sea surface, was expected to make the further removal of boulders by wave action an unacceptably slow process. This made the removal by artificial means (crane) a necessary operation.

From July until November 1997 (when all civil engineering work was suspended due to bad weather and the approaching winter season), the contractor used the land-based crane, positioned on the platform, to remove rocks from the bottom. This task was resumed in May 1998 and was completed in September 1998. By this time, practically all boulders had been removed from the sea bed within the reach of the mobile crane.

The removal of boulders from the bottom of the chamber was particularly difficult: indeed, since part of the chamber roof had already been concreted in 1997, the access with the crane was limited to only about half of the area.

3.2.2. DAMAGE TO THE FRONT WALL

A comparison of photographs of the front wall taken in November 1996 and inspections made in June 1997 showed that superficial damage over a considerable area above water level (especially on the eastern part of the wall) occurred during the winter 1996-97. This was attributed to impact of stones during storms. This kind of erosion did not occur (or was much lighter) during the following winter, after most of the boulders were removed from the sea bed (see above).

Some damage of a different kind was observed by divers in June-July 1997 on the front wall below water level, after the form work had been removed. Underwater photographs and video pictures were taken. A hole of irregular cross section was observed running across the 2-metre-thick front wall. It was located about 1 to 2 metres below water level, close to the eastern end of the front wall. Some damage was also found nearby, at about the same level, on the (eastern) side wall to which the front wall is attached. Some of the damage could possibly have been produced, during winter storms, by collision of boulders remaining from the temporary cofferdam and not yet totally removed from the gully. However, the most likely cause (especially in the case of the hole in the front wall) is defective underwater concreting during the construction work carried out in 1996: the concrete presumably did not reach properly the defective regions. This affected the structure behaviour in two different ways. Firstly, an undesirable flow of air (inwards or outwards depending on the inside air pressure) would occur through the hole whenever the latter becomes exposed by wave troughs. Secondly, the structure was weakened as compared with design conditions.

Profabril (the designer of the structure) was requested to study the problem from the structural point of view, and came to the conclusion that the hole was to be filled and, in addition, the front wall would have to be reinforced locally. A reinforcing structure was designed in July and August 1997: a beam, one metre thick and spanning the 12-metre width of the chamber, was to be concreted adjacent to the inner part of the front wall. The new structure would have to be properly attached to the existing front wall and, at its ends, to the side walls of the chamber. In this way, the thickness of the front wall, from the lower lip up to level about +3 m, would be increased from 2m to 3 m.

As most of the repair work would have to be done underwater, a temporary cofferdam would be necessary. The construction of a massive cofferdam made up of large boulders (like the one used in summer 1996) was avoided to speed up the work and reduce costs.

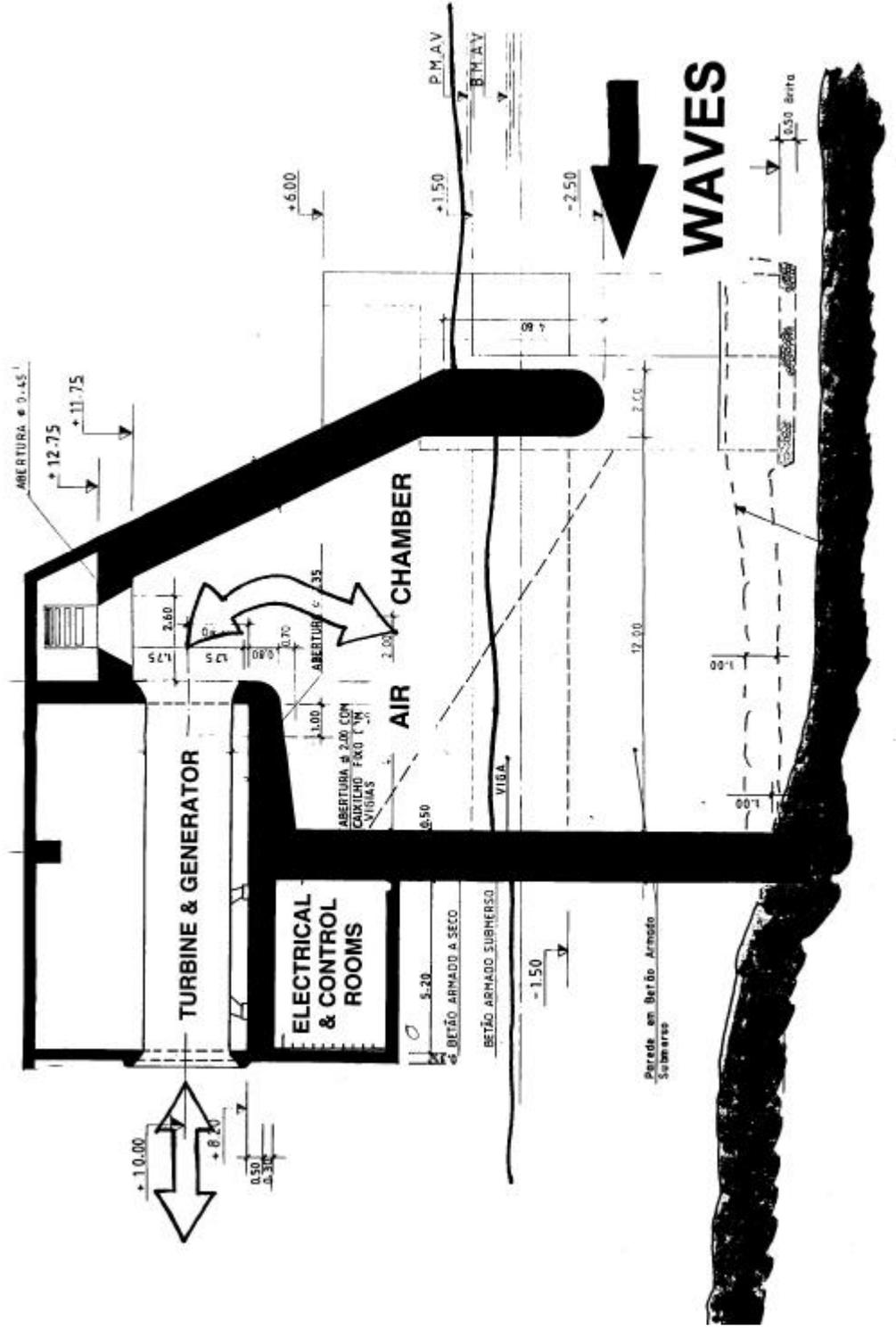
A temporary cofferdam made of 12m-long steel beams (500mm-I-cross section) mounted (at an angle of 30 degrees with the vertical direction) side by side, standing on the sea bed and leaning against the sloping front wall of the chamber, was discussed and found to be the most expedite and reliable way of solving the problem. This was the solution adopted by the contractor.

The repair work was completed in mid July 1998. Some minor repair work to the submerged parts of the inner wall of the chamber was done later while the cofferdam was still in place.

The temporary cofferdam was removed by mid-August 1998.

3.2.3. CONSTRUCTION OF THE CHAMBER STRUCTURE AND THE EQUIPMENT ROOMS

The construction of the chamber structure top was completed in summer 1997, with the exception of about half of the roof (eastern part) which was left to be concreted later in order to allow the repair work on the front wall to be carried out inside the chamber with the help of the crane.



The construction work in the turbine room started in May 1997. The construction of the electrical and control rooms started in June. In October 1997 the concreting of the floor, walls and roof of both rooms had already been completed.

When all civil construction work was suspended by the contractor in the beginning of November 1997, the dividing walls inside the electrical and control room, and the staircase had been built, and finishing work was going on inside both rooms. With some exceptions, the doors and windows, and the steel structure covering the roof entrance to the turbine room had already been manufactured.

The civil work, was resumed in May 1998, when the sea conditions became sufficiently calm. The access and the platform for the crane, which had been damaged by the sea during the winter season, were repaired. The crane was then brought back to its working area near the plant.

The foundations for the turbo-generator set, in the turbine room, were concreted in May. The floor of the electrical equipment room was finished in June.

The walls of the rooms downstairs were finished and painted during the first half of July.

It was recognized that the cables connecting the plant to the electrical grid of the island had to be protected from sea water in the vicinity of the structure. Several ways of doing it were envisaged. The adopted solution was to use three steel beams (I-500 mm beams that had been used to build the temporary cofferdam) welded together to form a 12-metre long duct that spans the distance from the plant structure to a concrete box on land. This was done in the second half of August 1998. Due to the vicinity of the airport runway, the rest of the cable had to be buried.

The supervision of the civil construction was done by Profabril.



Fig. 3.1. Front view of the plant (October 1998).



Fig. 3.2. Side view of the plant (October 1998). The access to the turbine room is through the open door.



Fig. 3.3. Back view of the plant building (October 1998). The steel duct protecting the electrical cable can be seen on the right.



Fig. 3.4. Turbine room, showing the bellmouth piece of the turbine duct before erection (July 1998).

4. MECHANICAL EQUIPMENT

4.1. WELLS TURBINE DESIGN

The aerodynamic design of the turbine was based on specifications resulting from the overall performance studies (see section 2.1.1. above). The quasi-three-dimensional code which was used combines a two-dimensional blade-to-blade flow analysis with a two-dimensional axisymmetric through-flow analysis. This code was incorporated into an iterative program for geometry optimization. Input: design (maximum) values of flow rate and available overall pressure drops, maximum allowed Mach number at rotor blade tip. Optimization criterion: minimum outer diameter. Output: inner and outer diameter, blade solidity, rotational speed, guide vane geometry, curve of efficiency versus flow rate. Results and experience gained in the project *Air turbine development and assessment for wave power plants* (contract JOU2-CT93-0333) were used. The main characteristics for the turbine are as follows:

Rotor

type	monoplane, fixed blades
maximum rotational speed	1500 rpm
minimum rotational speed	750 rpm
outer diameter	2.3 m
inner diameter	1.36 m
number of blades	8
chord	constant
rotor blade profile	NACA 0015 or similar

Stator

stator type	one row of fixed guide vanes on each side of the rotor
vane geometry	cylindrical shape, radially variable chord
number of vanes in each row	59

The detail mechanical design of the Wells turbine was carried out at IST. This included the air ducts and the frame system. In the design the following points were taken into consideration:

- ease of construction;
- the turbine shaft bearings (one on each side of the rotor) are to stand the aerodynamic axial thrust (maximum thrust: 22 kN);
- easy removal of the outer and inner casings for inspection, maintenance and monitoring;
- capability of removal and/or replacement of rotor blades *in situ*;
- flow disturbance due to structural elements across the duct annular area to be minimized;
- no shaft-supporting struts between the rotor and any of the guide-vane rows;
- moment of inertia of rotating elements: 600 kg m².

A report was produced by partner IST, with detail drawings, specification of materials and surface protection. Three assembly drawings (A3 size) of the turbine, duct system and machine bed are appended to this report.

4.2. STOP VALVE

An air valve is required in the duct connecting the turbine to the air chamber to stop the air flow through the turbine:

- (a) as a normal operational procedure whenever the plant is to be shut down;
- (b) to prevent the turbine from over-speeding or running-away if the turbine torque becomes excessive, or if the electromagnetic torque vanishes (electrical grid failure, or electrical failure in the power equipment) (this requires a fast-acting valve);
- (c) if mechanical failure in the turbine or generator, or overheating occurs (to be detected by vibration and temperature probes).

4.3. PROCUREMENT AND SUPPLY

After some inquiries were made, it was realized that only a few manufacturers would be prepared to supply the Wells turbine. So it was decided to prepare two different tender documents for the bidding process: (i) for companies that would supply the equipment based on their own mechanical design; and (ii) for companies that would simply manufacture the equipment according to given detail mechanical design (see above). The call for bids process was initiated in 1996. One company (Applied Research and Technology Ltd) submitted a proposal for the supply of the equipment manufactured following their own mechanical design. Four companies submitted proposals for the supply of the equipment according to the mechanical design given with the tender documents; two of them were prepared to revise the mechanical design (and one of the two would assume responsibility for the revised design as their own).

An order for most of the mechanical equipment was placed in September 1996 with the company Applied Research and Technology Ltd (ART), based in Inverness, Scotland. The equipment to be supplied included:

- one Wells turbine (rotor, guide vanes, bearings);
- mechanical coupling between turbine and generator;
- ducting (inner and outer ducts, noses, bell-mouths);
- a fast-acting stop valve (pneumatically actuated);
- supporting structure;
- piping system for the generator cooling air.

Following the order, ART went on with the detail design of the equipment.

Several modifications were introduced into the initial basic design. In particular, reinforced concrete was replaced by steel as the material for the duct connecting the turbine to the chamber.

The possibility of installing a brake was studied. This brake would act to prevent the turbine from running away and to slow it down to rest, especially in case of simultaneous failure of the electrical grid and of the stop valve. However this solution was later abandoned because of its cost and also because the stop valve was considered sufficiently reliable. Instead, it was decided to install a smaller, parking brake (to be applied at speeds smaller than 50 rpm).

Following a proposal by ART, it was decided to order a sluice gate, pneumatically actuated, to be installed in the ducting connecting the turbine to the air chamber. More precisely, it would be attached directly to the bell-mouth piece. The valve is closed during maintenance operations or whenever required (for example in stormy conditions). The fast-acting valve (of multi-vane type) is kept for use in operations requiring a short closing time.

ART shipped the sluice gate and the adjacent bellmouth (in advance of the remaining equipment) to the Island of Pico in August 1997.

The remaining mechanical equipment supplied by ART was shipped in October 1997.

4.4. ERECTION

The steel bellmouth piece (which makes the transition between the chamber and the turbine duct) was concreted into position on the turbine room wall in the second half of July 1998. The same was done with an identical piece for the second (variable rotor-blade-pitch) turbine (to be installed in 1999 within the framework of contract JOR3-CT95-0002). The sluice gate was then bolted to the first bellmouth piece in order to isolate the turbine room from the chamber. The bellmouth piece of the second turbine was closed by a reinforced steel plate.

The monorail winch was installed in August 1998. This was followed by the erection of the turbine, generator, multi-vane fast-acting valve and ducts, which was completed on 2nd October. The two air valves were then tested with their pneumatic system. These operations were performed by personnel from EDA and ART.

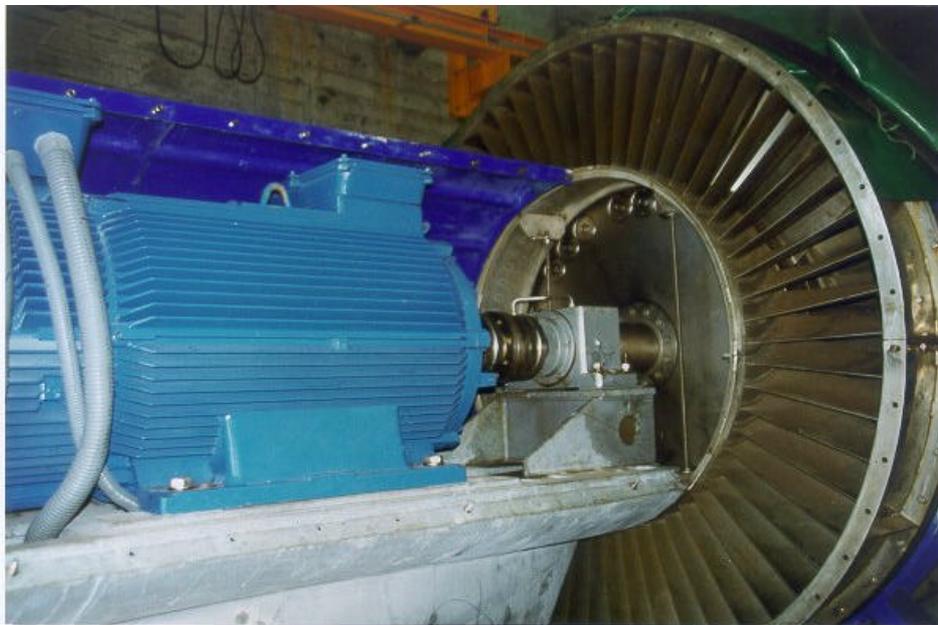


Fig. 4.1. Turbine and generator (October 1998).

4. ELECTRICAL EQUIPMENT

5.1. DEVELOPMENT OF NON-CONVENTIONAL EQUIPMENT

5.1.1. INTRODUCTION

The use of a variable speed electrical generator was one of the basic decisions made at the beginning of the project (Phase One) and one of its most important and innovative features. The capability of controlling the rotational speed N within a wide interval (in fact between the synchronous speed and about twice its value) enables the turbine to respond efficiently to a wide range of sea states (at best efficiency point, the flow

rate and the power are proportional to N and N^3 respectively), and also allows a temporary storage of excess available energy (by flywheel effect) with a short-term smoothing effect on the electrical power supplied to the grid.

Using a modified version of the asynchronous machine, whose technology is well established, is the simplest way of achieving that goal. The machine will perform as a generator at speeds above the synchronous speed and as a motor below that speed. By choosing the maximum speed as twice the synchronous speed, the generator slip factor s will vary between zero and minus one.

Let us assume that the current in the windings of the generator is allowed to reach the same maximum value as in the “original”, conventional machine at rated power and near-synchronous speed, and then increase the rotational speed to twice the synchronous speed. Since the maximum torque remains unchanged, the rated power of the machine is doubled. So, by using, as a starting point, a 200 kW / 750 rpm machine, we will be able to generate 400 kW at 1500 rpm.

It is known that, for an asynchronous machine, the rotor power P_r is $P_r = s P_e$, where P_e is the stator power. If $|s| = 1$, the rotor and stator powers are equal, and so, at twice the synchronous speed, half of the power output of the machine is delivered by the stator while the other half is supplied by the rotor. A power electronic converter of only 200 kW is needed in this case.

A set consisting of a 200 kW machine and a 200 kW converter will be able to generate a power of 400 kW, which, together with the capability of operating at variable speed, makes this choice a very convenient one.

In an asynchronous machine with slip energy recovery, the stator voltage and frequency are imposed by the grid, while the open circuit rotor voltage and frequency vary with the speed (they are proportional to the slip). At the synchronous speed ($s = 0$) they are equal to zero, and take the same values as the blocked rotor voltage and frequency at twice synchronous speed ($|s| = 1$).

The rotor current harmonics generated in the rectification will appear in the stator current. To reduce these harmonics, a 12-pulse diode rectifier is used and the rotor has two windings with an electrical phase difference of 30 degrees. To avoid the existence of 6 rings in the machine, the diodes are mounted in the rings, and the rotor voltage is collected as DC.

5.1.2. CURRENT SOURCE INVERTER

The power electronic converter adopted for this system is a Current Source Inverter (CSI) which has a variable DC voltage in its input and the grid voltage and frequency in its output. The CSI uses IGBTs with PWM control to deliver to the grid a current with very low harmonic content.

Figure 5.1 shows the overall diagram of the system. The stator voltage is 400 V, and the rotor voltage was chosen to have that same value at $|s| = 1$. The maximum DC bus voltage is 540 V. Each arm of the CSI uses a 1000A/1200 V IGBT.

Each IGBT has an 800 V over-voltage protection device at its terminals, to act as a clamp for the commutation transients. Special care was taken in the physical layout of the CSI to reduce the parasitic inductances responsible for the commutation energy to be dissipated. A slower IGBT OFF commutation compared to the ON, and a sufficient overlapping time, ensure that the DC current is transferred from one arm to the next one without generating high over-voltage transients.

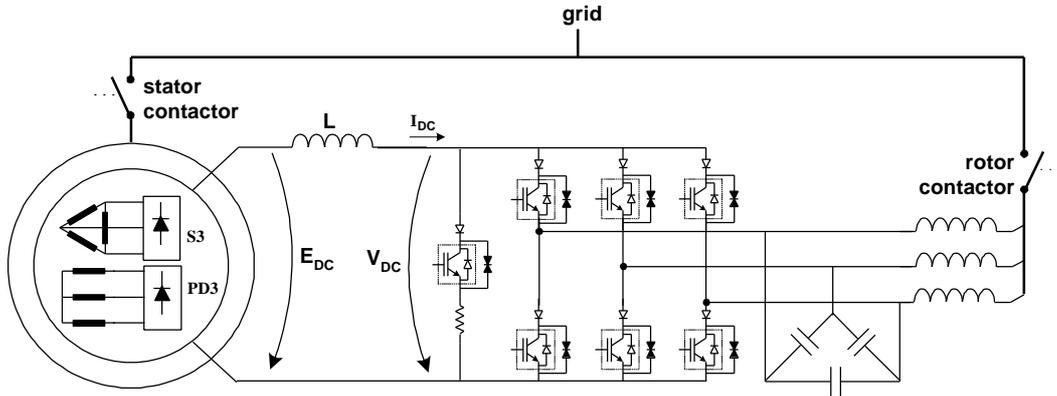


Figure 5.1: Overall diagram of the system.

A filter reactor is used in the DC bus to supply the CSI with smoothed DC current and to limit the CSI switching frequency currents that the rotor windings absorb. The AC capacitors are necessary for the CSI commutation, and, together with an inductor, form a low-pass filter for the CSI output current. This filter could be made relatively small by the use of a switching frequency of 2.25 kHz, which is a normal switching frequency for this type of IGBTs. A protective IGBT with a resistor is added in the DC bus, which is used to give an alternative path to the current when the CSI must stop as a consequence of any failure or emergency. When a fault in the CSI is detected, this IGBT is turned ON, the CSI IGBTs are turned OFF, and the contactors are opened. This circuit only dissipates power in the resistor for the time necessary for the stator contactor to open, and the rotor current reach zero.

The CSI is controlled by a microprocessor, which generates a PWM in order to vary the DC voltage from zero to 540 V ($V_{DC} = 540i_m$), where i_m is the modulation index.

In this way, the rotor current is controlled according to

$$I_{DC} = \frac{1}{L} \int [E(t) - V_{DC}(t)] dt + \frac{1}{R} [E(t) - V_{DC}(t)],$$

where L and R are equivalent parameters for the circuit, E is the rotor no-load DC voltage, V_{DC} is the DC voltage at the inverter input, and the semiconductors are assumed ideal elements. In steady state, this current has a DC component corresponding to the second part of the equation, and an AC component that corresponds to the first part. It can be shown that for this system, the AC component is constant at all powers above the point where I_{DC} never reaches zero.

By controlling the DC current, the CSI controls the rotor current, and so the torque and consequently the power converted to the grid.

Each modulation index is stored in a table in non-volatile memory, instead of being calculated in real time, saving processing time, and so allowing the microprocessor to perform other tasks related to the control of the system.

The PWM pattern, in conjunction with the switching frequency and the filters, reduces the current harmonics injected into the grid to about 2% THD.

5.1.3. SYSTEM CONTROL

The primary energy source (wave energy) is known to vary randomly, during a wave cycle, from wave to wave, with changes also produced by wave grouping. The power oscillates at twice the wave frequency, with an amplitude that varies from wave to wave. The power conversion system has some mechanical inertia (due mostly to the rotating parts of the turbo-generator set), and the speed is already a filtered image of the chamber pressure. The control strategy minimizes the fluctuations of the electrical power delivered to the grid and so the electrical power is a damped image of the speed.

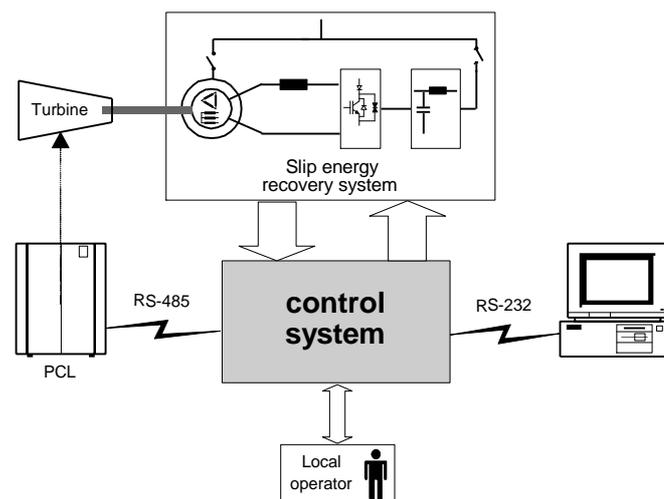


Figure 5.2. Control system architecture.

Figure 5.2 shows the system control architecture. The control system is based on a 16 bit microprocessor, which handles the analogue and digital signals acquisition and conditioning. Besides generating the PWM, it also controls the system, in order to optimize the generated power. This microprocessor adjusts the electrical power to the turbine optimum power, which depends basically on the rotational speed.

Since this is a pilot plant, a study has been carried out to find out a control algorithm that optimizes the plant's performance.

Different algorithms, relating instantaneous electrical power (or torque) to instantaneous rotational speed, are stored in non-volatile memory as a table. Downloading each one by serial interface, every algorithm can be tested and compared with others.

The microprocessor uses one of these algorithms at a time. The choice is made by the operator, or automatically since the microprocessor is permanently communicating with the plant main PLC. In order to perform this, the control system includes an RS485 interface for connection to the plant PLC, an RS232 local interface to download data, and a LCD display and keyboard for local operation.

5.2. SUPPLY AND ERECTION

The unconventional electrical and control equipment was developed by partner EFACEC Sistemas de Electrónica SA, as part of the R&D activity within the framework of the present contract, as reported above. The supply was made through another company within the same group: EFACEC Engenharia SA. The same company also supplied most of the conventional electrical equipment:

- power transformers;
- medium voltage switch board;
- low voltage switch boards;
- rectifiers and batteries;
- power cables and ducts for the cables.

The generator and the electronic converter were tested in factory in May 1998, after which the equipment was shipped to the island of Pico, where it was stored prior to erection.

The electrical equipment and circuit concerning illumination, wall sockets and ventilation were installed in the first half of August.

The erection of the main (conventional) equipment in the electrical room started in mid August. It included the 30 kV metal-clad switchgear (with two compartments), the 630 kVA transformer, the general AC board, and the 48 V battery and its battery charger. The generator was installed and coupled to the turbine later.

An accident occurred on 5th September 1998 when the erection of the equipment in the electrical room was almost completed: some of the conventional electrical equipment (including the general AC board) was damaged by sea water, and had to be returned to factory for repair or replacement. The start up of the plant was delayed by several months for this reason and had not yet taken place at the time of writing this report.

6. MONITORING

The pilot plant monitoring equipment is required to collect data for the plant's control (by the Programmable Logic Controller or PLC), for R&D, or for both purposes.

The quantities to be measured are the following (with the indication of their use):

- (a) Loads on front wall due to wave action (R&D)
- (b) Incident waves (R&D)

- (c) Internal water free-surface level (R&D)
- (d) Chamber air pressure (control, R&D)
- (e) Air flow rate and pressure drop through the turbine (R&D)
- (f) Rotational speed (control, R&D)
- (g) Electric power output (control, R&D)
- (h) Electric current, voltage, etc. (control, possibly also R&D)
- (i) Failure indicators (bearing vibrations, generator temperature, etc.) (control)

6.1. INCIDENT WAVE MONITORING

The incident waves will be measured by three pressure transducers located at the sea bottom in front of the device at a distance of about 20 m. The transducers will be attached to the vertices of a triangular steel structure that will stand on the sea bed and will ensure that the transducers will remain in place (and keep their relative positions) regardless of the currents at the bottom. This configuration will allow the incident and reflected waves to be computed separately from the data processing.

The installation of the transducers on the sea bottom had to wait until the dredging of the gully (removal of boulders with the crane) was completed, which did not occur until the end of September 1998. By this time the sea conditions were no longer calm enough for underwater work to be done by divers. As a result the installation of the probes was postponed until spring of 1999.

6.2. WAVE IMPACT FORCES MONITORING ON THE FRONT WALL

A system to measure the impact loads due to waves breaking on the front wall of the plant was developed and designed by the Queen's University of Belfast (QUB).

Because the impact pressures are of very short duration, a high-rate data acquisition system is needed. For this reason, it was decided to have a separate data acquisition system for this purpose. The probes, the supporting structure and the data acquisition system were manufactured in Belfast at the QUB.

The system will be installed (in particular the probes will be fixed to the front wall) in the spring of 1999. By then it is expected that the winter storms will have cleaned the bottom of the gully and removed most of the remaining stones whose impact on the front wall would otherwise have damaged the probes.

6.3. INSIDE WATER LEVEL MONITORING

The level of the water free-surface inside the chamber is measured by a system Milltronics Airanger SPL. The ultrasonic transducer XPS-30 was installed at level +7m at the ceiling of the chamber (under the machine room), and is supported by a stainless steel tube that crosses the concrete plate. Figure 6.1 shows the probe assembly before and after installation in site. The processed signal (level indication) is transmitted to the data acquisition system located downstairs in the control room.

6.4. CHAMBER AIR PRESSURE MONITORING

The air pressure inside the chamber is measured by two identical pressure transducers "SMAR LD 301" installed on the floor of the turbine room at level 8.20 m. One of the transducers will be connected to the PLC for control purposes, while the other is dedicated to the monitoring system. The latter one is presently connected to the data acquisition system.

The first data were recorded on 6th November 1998.



Fig. 6.1. Milltronics ultrasonic transducer assembly for water level measurement, before and after installation (the turbine room floor level is +8.20m).

6.5. TURBINE AIR-FLOW MONITORING

The air flow rate through the turbine duct and the pressure drop across the turbine are measured by a system of total-pressure tubes and static pressure taps located on both sides of the turbine. There are 9 total-pressure tubes on each side of the turbine: their location is defined by the combination of three radial and three circumferential positions. The static pressure taps are located on the out casing of the duct, 120 degrees apart from each other. The pressure tubes and taps are connected by flexible plastic tubes to transducers installed in the turbine room.

6.6. PLANT ELECTRIC POWER OUTPUT MONITORING

The electric power output of the plant is monitored at the 500 kVA transformer by measuring the currents and voltages at the three AC lines.

6.7. DATA ACQUISITION SYSTEM.

The data acquisition system is located in the control room. The signals coming from the "marshalling" box are connected to the terminal PCB of the data acquisition board Data Translation DT 3002 with 32 channels, installed in a Pentium PC with 233 MHz and 64 Mb of RAM.

The data acquisition software named *PICO98_1.VEE* was developed at INETI based on HP - VEE and DT VPI applications. This software collects data from the 32 channels at a specified rate (typically 2 Hz). The output is presented in numerical and also graphical form. The wave data outside and inside the chamber is processed online

yielding the following statistical information: significant height H_s , energy period T_e , peak period T_p and power per unit length P .

The software *PICO98_1.VEE* allows the information to be shown on the main screen of the data acquisition system. The processed data are recorded on disk for periods of 20 minutes at three-hourly intervals. The hard disk can store about 4 months of data. The information can also be stored weekly in CD ROM. The data acquisition system is connected to the outside world via MODEM.

A guide of the software was produced with the complete description of its capabilities. Figure 6.2 presents the main screen of the data acquisition system with *PICO98_1.VEE* software. Data started to be collected on 6th November 1998.

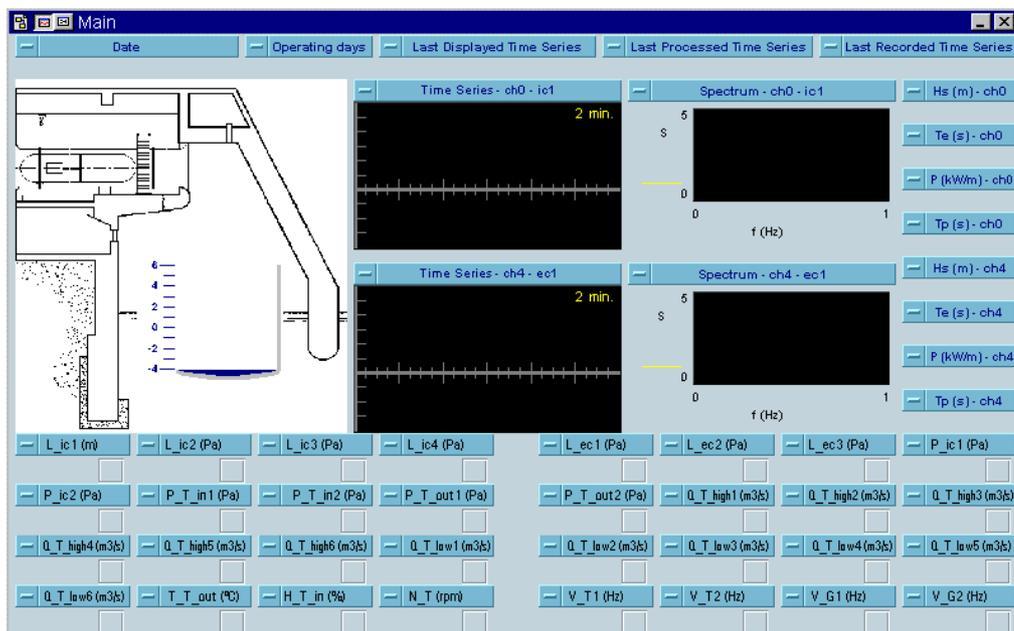


Figure 6.2. Main screen of the data acquisition system with software *PICO98_1.VEE*.

7. PLANT CONTROL

7.1. ROTATIONAL SPEED CONTROL

7.1.1. INTRODUCTION

The air turbine for an OWC plant is subject to flow conditions (randomly reciprocating flow) which, with respect to efficiency, are much more demanding than for turbines for almost any other application. The turbine, on one hand, is required to extract energy from air whose flow rate, in each of the two directions, oscillates between zero and a maximum value, which in turn has an extremely large variation from wave to wave and with sea conditions. On the other hand, at fixed rotational

speeds, turbines in general, and Wells turbines in particular, are capable of operating with good efficiency only within a limited range of flow conditions around the best efficiency point (b.e.p.). The power output of Wells turbines is known to be low (or even negative) at small flow rates (the flow rate passes through zero twice in a wave cycle). However, it drops sharply for flow rates above a critical point; this means that the turbine is expected to perform poorly in very energetic sea states or whenever violent wave peaks occur, the decay in performance being due to aerodynamic losses produced by rotor blade stalling. An efficient way to widen the response of the turbine (and hence of the plant) to the varying power level of the waves consists in using variable rotational speed N . This enables the turbine to respond efficiently to a wider range of sea states: indeed, at b.e.p., the turbine flow rate and power output are known to be proportional to N and N^3 , respectively. If N is allowed to double, the turbine power range is multiplied by eight. In addition, this capability allows a temporary storage of excessive available energy (flywheel effect) and has a short-term smoothing effect on the electrical power supplied to the grid. The turbine efficiency, and the quality and total amount of energy produced, will depend strongly on how the instantaneous rotational speed is controlled (this is done through the programmable logic controller or PLC by acting on the instantaneous electrical generator torque); the randomness of the waves and the inertia of the rotating parts makes this no easy task.

In a simplified way, we may consider the following time-scales associated with wave power variations: (i) the short period oscillations in the order of half a wave period (4 to 8 s); (ii) the medium term variations associated with wave grouping, having a time scale of some tens of seconds; (iii) the long term variations connected with changes in sea state. If the range of operating rotational speed is wide enough (say maximum-to-minimum speed ratio is about two), the kinetic energy storage is expected to (more or less perfectly) filter the short-period oscillations and help solving the problems due to wave grouping.

From the turbine performance viewpoint, and in terms of values averaged over a few wave periods, the rotational speed should be adjusted to the power level of the waves (and consequently to the pneumatic power available to the turbine): it should be controlled in a way that optimizes the turbine performance (i.e., maximizes the average efficiency and the energy produced).

7.1.2. THEORETICAL MODEL

A theoretical model was developed to simulate the plant's performance and assess the effectiveness of the control strategies. The OWC wave energy device is fixed with respect to the sea bottom. The geometry of the device and of the surrounding submerged solid boundaries is arbitrary, and the waves incident upon the device are supposed, in general, to be irregular. Let $p_{\text{atm}} + p(t)$ be the air pressure (assumed uniform) inside the chamber (p_{atm} = outside atmospheric pressure) and $q(t)$ the volume flow rate displaced by the motion of the internal free-surface of water. Assuming that linear water wave theory applies, we may write $q(t) = q_r(t) + q_i(t)$, where $q_r(t)$ is the radiation flow rate due to the air pressure oscillation $p(t)$ in the

absence of incident waves, and $q_i(t)$ is the diffraction flow rate due to the incident waves if the air inside the chamber were kept at atmospheric pressure (i.e., $p = 0$). If the spring-like effect due to air compressibility is accounted for by a linearized isentropic relationship, then the equation to be solved in the time domain is

$$\frac{dp}{dt} = -w \frac{p_{\text{atm}} \mathbf{g}}{\mathbf{r} V_0} + \left[\int_{-\infty}^t g_r(t-\mathbf{t}) p(\mathbf{t}) d\mathbf{t} + q_i(t) \right] \frac{p_{\text{atm}} \mathbf{g}}{V_0}. \quad (1)$$

Here, w is the air mass-flow rate through the turbine (positive for outward flow), V_0 is the volume of air in the chamber (undisturbed conditions), \mathbf{r} is the outside air density and $\mathbf{g} = c_p/c_v$ is the specific heat ratio for air. The convolution integral represents the radiation flow rate $q_r(t)$; the function $g_r(t)$ that appears in the integral depends on the geometry of the system and is assumed known either from measurements or theoretically. We also suppose that $q_i(t)$ is known from the incident wave field, which, in general, requires solving a diffraction problem.

Neglecting the effect of the variations in the Reynolds and Mach numbers, the performance characteristics of the turbine can be written in dimensionless form as $\Phi = f_w(\Psi)$, $\Pi = f_p(\Psi)$. Here $\Phi = w/(rND^3)$, $\Psi = p/(rN^2D^2)$ and $\Pi = P/(rN^3D^5)$ are dimensionless coefficients of flow, pressure and power, respectively, D is the outer diameter of the turbine rotor, N its rotational velocity (radians per unit time) and P the power output. The functions f_w and f_p depend on turbine geometry (but not on its size or rotational speed). We assume here that f_w is an odd function and f_p an even function, and that these functions are known (possibly from model testing). So, for given D and \mathbf{r} , the flow rate w and the power P can both be considered as known functions of N and p .

During normal operation, the aerodynamic torque $L_t = P/N$ upon the turbine due to the air flow is irregular and strongly oscillating. We may write

$$\frac{dN}{dt} = \frac{1}{I} [L_t(N, p) - L_e], \quad (2)$$

where L_e is the instantaneous value of the electromagnetic torque and I the moment of inertia of the rotating parts of the turbo-generator set.

There are several factors to be taken into account when devising and optimizing the control strategy: (i) allowed rotational speed range $N_{\min} \leq N \leq N_{\max}$ (limits are imposed by the mechanical and electrical equipment); (ii) aerodynamic performance of the turbine: the rotational velocity should approximately match the sea conditions in order to maximize the turbine efficiency (N should be higher in more energetic sea conditions); (iii) energy quality and allowable fluctuations in power delivered to the grid; (iv) efficiency of the wave-to-air conversion (changes in rotational speed modify the turbine flow-versus-pressure curve, and indirectly influence the hydrodynamics of

the wave-to-air energy conversion); (v) realistic control procedure: the control algorithm should have, as input, easily measurable quantities (e.g. rotational speed, air pressure in the chamber), and should be adequate for implementation on-line in the PLC of the plant.

We mentioned above that, for a given turbine, the power output P is a function of p and N . Then, for any instantaneous value of p , the value of N for which the turbine is to deliver maximum power should satisfy $(\partial P/\partial N)_p = 0$, from which we can easily obtain $2\Psi f'_p(\Psi) - 3f_p(\Psi) = 0$, an equation whose solution we denote by Ψ_{op} . If it were possible to control the instantaneous rotational speed N without restrictions, then the best turbine performance (maximum power output) would be achieved at $N = |p|^{1/2} (\mathbf{r}D^2\Psi_{\text{op}})^{-1/2}$. However we should not forget that N must satisfy the condition $N_{\text{min}} \leq N \leq N_{\text{max}}$. In addition, even without this restriction, the inertia of the turbo-generator set would make it practically impossible for the rotational velocity to follow the oscillations in pressure according to equation above. This means that, in practice, Ψ cannot be kept constant and equal to Ψ_{op} . Indeed, Ψ will oscillate, and the same can be said of the turbine power coefficient $\Pi = f_p(\Psi)$.

A control strategy can be devised in which Π is allowed to oscillate about some mean value, which we denote by Π_{av} . The numerical value of Π_{av} which maximizes the energy produced by the turbine (and which should be expected not to be very different from, but necessarily somewhat smaller than, $f_p(\Psi_{\text{op}})$) would have to be established by numerical simulations or experimentally. Now, equation (2) shows that the values of the turbine torque L_t and the electromagnetic torque L_e , averaged over any sufficiently long period of time (say several wave periods), are approximately equal. The control strategy consists in setting the instantaneous value of the dimensionless torque coefficient (or power coefficient) of the generator $L_e/(\mathbf{r}N^2D^5)$ equal to a constant; more precisely, equal to what has been defined as Π_{av} . For fixed values of \mathbf{r} and D , this is equivalent to writing $L_e = CN^2$, where C is a constant. We note that a control strategy based on this equation would not ensure that the condition $N_{\text{min}} \leq N \leq N_{\text{max}}$ is satisfied. Therefore a modified expression has to be devised for L_e . A way of doing this is to write

$$L_e = C \left[1 + \left(\frac{\mathbf{a}N_{\text{max}}}{N_{\text{max}} - N} \right)^b \right] \left[1 - \left(\frac{\mathbf{n}N_{\text{min}}}{N - N_{\text{min}}} \right)^q \right] N^2. \quad (3)$$

The first term between the square brackets ensures that N_{max} is not exceeded, whereas the second term ensures that the rotational velocity does not drop below N_{min} .

The (positive) parameters C , \mathbf{a} , \mathbf{b} , \mathbf{n} and \mathbf{q} are to be optimized (the optimized values are expected to depend weakly on sea state), or at least suitable numerical values are to be chosen for them.

Since the only control variable is the rotational speed N , this control strategy can be implemented easily. The proportionality to N^2 ensures that the average power of the generator adjusts itself to the incident wave power level. The oscillations in rotational speed, and consequently also in the electric power output, will decrease with increasing moment of inertia of the rotating parts.

Numerical results were obtained for an OWC representing, in a simplified way, the Pico pilot plant. An irregular-wave spectrum was adopted which was regarded as representative of the wave climate at the plant site in the Azores, the corresponding average power being 20.9 kW/m. Numerical simulations were performed with different sets of values for the parameters C , \mathbf{a} , \mathbf{b} , \mathbf{n} and \mathbf{q} that appear in equation (3). In a first optimization step, the rotational speed limits were ignored, and \mathbf{a} and \mathbf{n} were set equal to zero in algorithm (3); under such conditions, the value $C = 0.025 \text{ N ms}^{-2}$ was found to approximately maximize the produced energy. Numerical results are shown in Figs. 7.1 and 7.2, for $C = 0.025 \text{ N m s}^2$, $\mathbf{a} = 0.05093$, $\mathbf{b} = 2.0$, $\mathbf{n} = 0.0191$ and $\mathbf{q} = 4.0$. The numerical simulations showed that a compromise has to be reached between energy quality and plant efficiency (or equivalently quantity of energy).

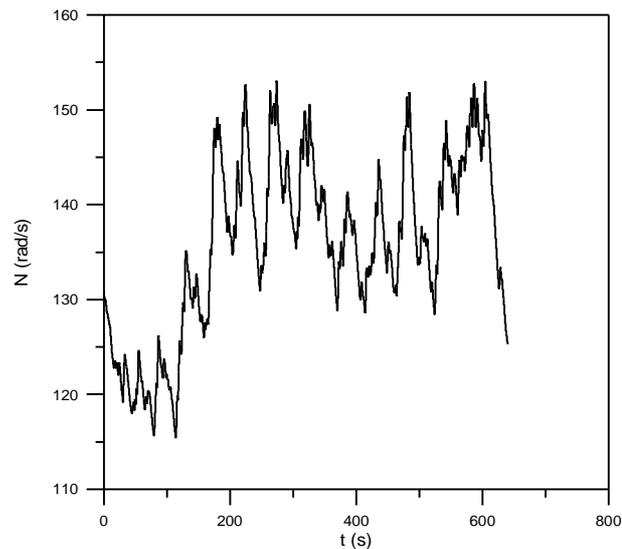


Figure 7.1. Rotational speed variation in irregular waves, with $C = 0.025 \text{ Nms}^2$, $\mathbf{a} = 0.05093$, $\mathbf{b} = 2.0$, $\mathbf{n} = 0.0191$ and $\mathbf{q} = 4.0$.

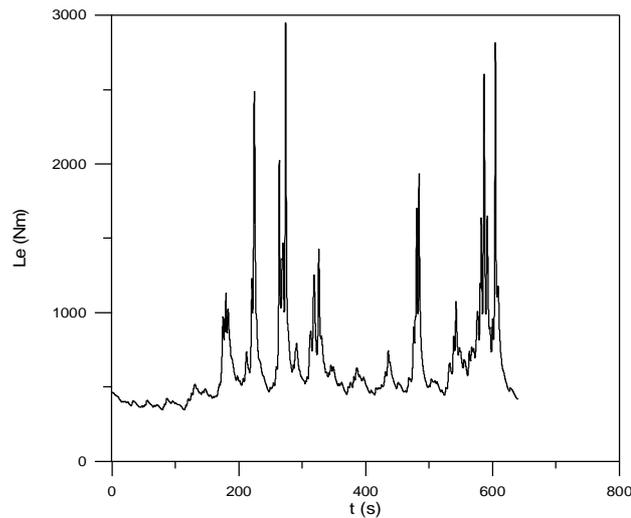


Figure 7.2. Electric torque variation in irregular waves, with $C = 0.025 \text{ Nms}^2$, $\mathbf{a} = 0.05093$, $\mathbf{b} = 2.0$, $\mathbf{n} = 0.0191$ and $\mathbf{q} = 4.0$.

7.1.3. WAVE-TO-WIRE MODEL

An alternative approach was also developed, which combines the theoretically based results of section 7.1.2 with experimental data.

The objective of the study is similar to the one presented in the previous section. A time-domain model of the plant, from wave-to-wire is used. Here, the numerical values of the impulse response function, g_r , in equation (1), were obtained from results of laboratory tests on a 1:35 scale model of the actual plant and surrounding coastline, rather than based on analytical expressions for a simplified geometry. The computer simulations were run for 44 sea states, representative of the wave climate at the plant site. The computed performance of the plant for each sea state was used to assess the goodness of the control procedure under study. Mechanical and electrical losses and the presence of a relief-valve have been modelled and taken into account. It was assumed that the cross-sectional area of the relief valve (at fully open position) is large enough to ensure that the turbine flow rate does not exceed the value at which aerodynamic rotor-blade-stalling occurs.

In what follows, the time variation in electrical power delivered to the grid is required not to exceed 50 kW/s, a limit recommended by the local utility (EDA). In addition the rotational speed is to be kept within the interval $N_{\min} < N < N_{\max}$.

Three control algorithms were tested: (i) an algorithm very similar to the one given by equation (4); (ii) a control algorithm based on a reference value of the rotational speed; and (iii) a mixed control algorithm combining (i) and (ii).

The control algorithms were compared with each other and also with reference values. The latter values were obtained by keeping the rotational speed constant and equal to the value that maximises energy production within each of the 44 time series.

The results of simulations indicate an adequate control algorithm can be written in the form

$$L_e = CN^2 \left[\frac{N_{\min} - N}{N_{\min} - N_{\text{opt}}} \right]^{10} \quad \text{for } N < N_{\text{opt}}, \quad (5a)$$

$$L_e = CN_{\max}^2 \left[\frac{N - N_{\text{opt}}}{N_{\max} - N_{\text{opt}}} \right] + CN^2 \left[1 - \frac{N - N_{\text{opt}}}{N_{\max} - N_{\text{opt}}} \right] \quad \text{for } N > N_{\text{opt}}. \quad (5b)$$

An approximate optimization procedure yielded $C = 0,13 \text{ Nms}^2$ and $N_{\text{opt}} = 135 \text{ rad/s}$.

The different control algorithms analysed produce very similar values of annual production of electrical energy. This indicates that the control strategy optimization is not a critical issue from that point of view, and also that there is margin to improve the quality of the supplied electricity, i.e., to reduce the wave-to-wave oscillations in electrical power output.

7.2. PROGRAMMABLE LOGIC CONTROLLER (PLC)

The control of the plant is achieved by means of the programmable logic controller or PLC. The PLC will control the start up, shut down and emergency operations, and will also control the plant under normal running conditions. The PLC was manufactured by EFACEC Sistemas de Electrónica SA and was supplied by EFACEC Engenharia SA.

Several sets of instructions were established and implemented by on the PLC, namely:

- Start-up:
 - a) the plant had been shut down due to insufficient wave power level;
 - b) the plant had been shut down due to excessive wave power level.
- Shut down due to insufficient wave power level
- Emergency shut down.
- Control under normal running conditions.

8. CONCLUSIONS. EXPLOITABLE RESULTS

The construction of the Pico plant was an important step in the development of wave power technology. It was the outcome of the joint effort from research institutions (including universities), industrial companies and utilities.

Although it is a R&D facility, the plant equipment was designed and/or specified as for an industrial unit, with 25 years specified as the life-span for the major items of mechanical and electrical equipment. The plant is fully automated and will be connected to the island's grid on a permanent basis.

At the time of writing this report, the plant had not yet started operation. This was due to an accident which occurred in September 1998 and delayed start up, as reported above in section 5.2. For this reason not many comments can be made at this time about actual plant performance.

Building a plant in a small and remote island is a typical application of renewable energy technology. The relatively high unit-costs of electrical energy from existing conventional plants enhances the competitiveness of renewable energies in general, and wave energy in particular.

On the other hand, the remoteness of the site introduced additional constructional problems, not all of which had been fully foreseen at the beginning of the project. This was the case of considerably higher costs of civil construction, and the vulnerability to delays whenever constructional or erection problems required materials, equipment and spare parts to be shipped from the main land. This was aggravated by the limited number of months yearly when construction work can be performed in a very exposed site.

The particular site in the island was found to be a good choice from the view points of wave energy resource (good exposition and natural concentration of energy) and access by land. In spite of the easy access, the in-situ construction of the structure was found to be costly and difficult, and is to be avoided if alternative solutions are available (this depends on the availability of facilities, for example the vicinity of a large shipyard or an adequate slipway).

It should not be forgotten that the high share of the civil construction in the total cost of the plant also reflects the role required from the plant, which was not designed as a simple commercial unit, but rather as a R&D facility to be used as a testing platform for power and control equipment (the turbine room is large enough to accommodate two turbine-generator sets).

Although only results from performance simulations are available at this time (rather than measured data from the actual Pico plant performance), it seems reasonable to conclude that reducing the plant's construction costs (especially the civil construction) is clearly the most important factor if second-generation OWC plants are to be competitive with more conventional technologies in terms of energy unit costs. The contribution from improving the energy chain conversion efficiency, although important (especially if achieved at no cost or at little extra cost), is expected to be a lesser factor. Alternative civil constructional methods, series production and the use of standard equipment whenever possible could be effective ways of reducing costs.

The main exploitable results of the project are:

- The know-how concerning wave power plant design, namely site selection, resource characterization, basic studies and design, structural design, equipment design and/or specification; the know-how resulting from plant monitoring, and performance and cost analysis. This can be used in: (i) the planning of wave energy utilization; (ii) the conception, design and construction of second-generation plants; (iii) the design and manufacture of wave power plant equipment. This know-how is in many ways unique, since it concerns the only existing full-sized wave power plant designed to be operated as an industrial unit.

- The power electronics technology for variable-speed generation: an asynchronous machine driven by a turbine at variable speed (between the synchronous speed and about twice its value) can be used to generate electrical power at the grid's constant voltage and frequency.
- The electrical energy supplied by the pilot plant to the island's grid (about 0.9-1.0 GWh/year or 7-8% of its annual consumption) is itself an exploitable result of the project.