

Control Strategy Development for an Inverter Controlled Wave Energy Plant

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Abstract This paper will introduce the Energetech wave energy conversion system and describe its main elements of structure, turbine, generator, instrumentation and control systems. The concept of a parabolic wall which focuses the wave energy onto an oscillating water column (OWC) will be shown. The OWC converts the wave motion to pneumatic energy and then to kinetic energy in air flows suitable for mechanical conversion by the Energetech variable pitch turbine.

The paper will show the main points of the station design which is due to have its first pilot plant commissioned by end 2004, 100km south of Sydney, Australia. The paper will describe the development of a wave to wire simulation used to rapidly test various station configurations and control scenarios. The model described will be shown as the result of several years of rigorous study involving scale systems, tank testing and computational fluid dynamics.

Finally, the use of an inverter controlled variable speed drive will be discussed as the means of power take-off for the Energetech turbine. The control strategies developed using this system and their application in wave energy will be presented using the results of the wave to wire simulation.

Key words

Wave energy, variable pitch turbine, inverter control, generation, power conversion

1. Introduction

The concept of converting ocean waves energy into electricity is not a new idea. In fact the first European patent for a wave energy device dates from 1799. However, the approach adopted by Energetech is novel and will enable rapid commercialisation of the technology. Figure 1 shows the elements of the Energetech system which comprise of structure, turbo-machinery and electrical systems. The picture shown is taken from a computer generated image of the full-scale design. The system is based on the well-known concept of the Oscillating Water Column (OWC), which is considered amongst the most commercially viable

concepts for ocean wave energy conversion. In such systems, the waves impinge on a partially submerged chamber that extends from slightly below the mean water level to some height above the surface.

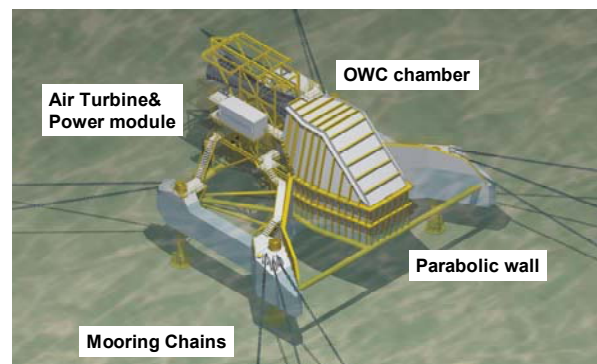


Figure 1 -The elements of conversion

The bottom of the chamber is open to allow water to enter. Wave induced vertical oscillations on the outside induce attendant vertical motions inside the chamber. As the internal water column oscillates, it displaces the air above causing a bi-directional flow past an aerodynamic turbine. Power is produced by a generator coupled to the turbine.

A. The parabolic reflector walls

The basic OWC method has been significantly improved by Energetech through the introduction of several novel performance-enhancing features. The patented Energetech system incorporates a parabolic-shaped wall that allows capture of a wide swath of incident wave energy, thus increasing the production capacity of a single device. As shown in Figure 2, the parabola serves to concentrate wave energy, thereby increasing wave heights in the vicinity of the focal point. The centre of the OWC is situated at the focal point of the parabolic wall such that the amplified waves are concentrated at the chamber. The reflector walls also have the advantage

that they allow efficient conversion from waves incident over a range of angles.

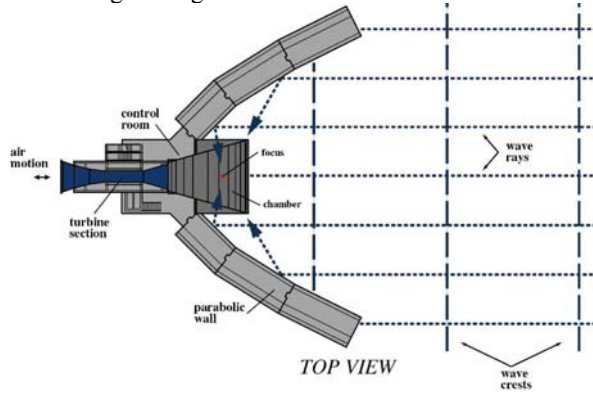


Figure 2 - Parabolic wall wave focusing

B. The Oscillating Water column

Figure 3 shows the OWC located at the focal point of the parabolic reflector. The vertical water oscillations within the chamber serve to alternately compress and decompress the air above. The associated pneumatic energy is in turn converted to kinetic energy by a convergent nozzle section that accelerates the air flow.

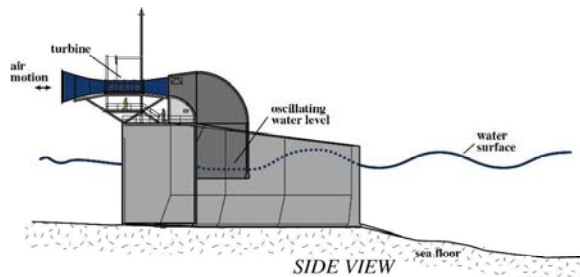


Figure 3 - OWC and turbo-machinery

The OWC essentially converts the hydrodynamic energy into pneumatic energy suitable for conversion by a turbine. It also works as a gearbox converting the slow motion of the water surface to high speed air-flows. However, the air-flow produced is bi-directional and time varying.

C. The Energetech Turbine

The bi-directional air flow inherent to OWC systems requires the use of an effective self-rectifying turbine. Most OWC designs to date have employed a fixed-pitch Wells turbine [1][2] however, extensive research has also been conducted on self-rectifying impulse turbines. Each type of turbine has unique operational benefits and performance characteristics, with none yet emerging as being obviously better in all respects. While being generally robust due to a lack of mechanical complexity, both turbines are subject to performance limitations over the range of expected flows.

One method of improving turbine performance in bi-directional oscillating flows is to allow the blade angle to change as the flow varies. This concept has been explored for variable-pitch Wells turbines [3][4] and has

been developed into a prototype by the University of Edinburgh, with the intention of testing in the OWC plant at Pico, Azores. Under its own initiative, Energetech Australia, in collaboration with the University of Sydney, has designed a new variable-pitch turbine with unique operational characteristics [5]. A picture of a full-scale Energetech turbine is shown in Figure 4.

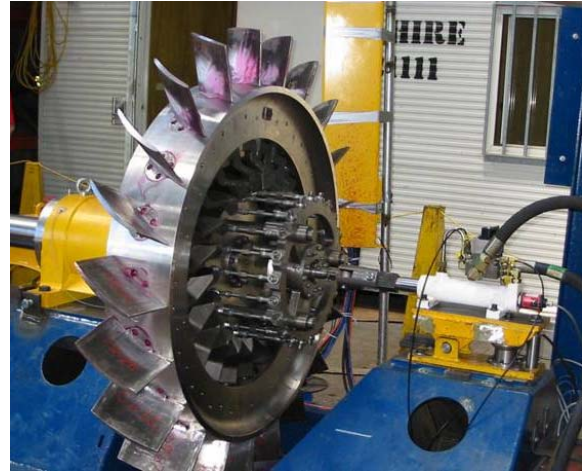


Figure 4 - Full scale Energetech turbine

This turbine is not modelled on either Wells or impulse turbine configurations, and is different from both in many respects. The picture in Figure 4 not only shows the turbine and blades but also shows quite clearly the actuation mechanism which is used to vary the pitch of the blades. As the airflow changes direction the blades of the turbine must swap orientation. The degree of pitching required is shown in cutaway in Figure 5. The angles shown are limitations imposed on the actuation due to this particular design of the turbine. A second generation turbine has been designed which does not have this limitation.

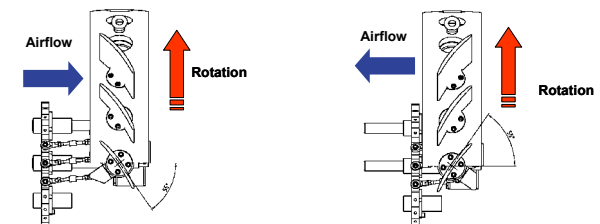


Figure 5 – Energetech turbine pitching regime

As well as the pitch changing when the flow direction changes, the pitch can also be varied throughout the wave cycle in order to produce a demanded torque. This can be achieved using a control system feed with an array of flow sensors.

D. Power Module

The final part of the conversion system is the power module, where the turbine torque is converted to electricity. A schematic of the power module is given in Figure 6. This shows a shut-off valve, an outer diffuser and an inner nacelle. The shut-off valve isolates the turbo-machinery from the OWC and will be closed when

the station is not generating. It can also close without power on emergency stop and loss of mains.

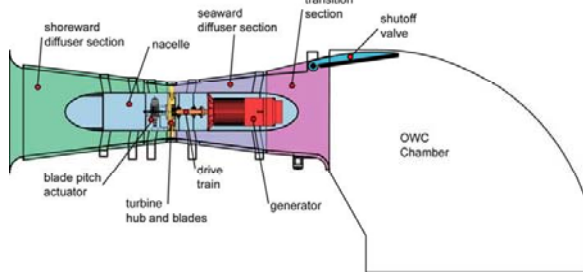


Figure 6 - Power train schematic

The outer diffuser section aerodynamically accelerates then decelerates airflow through the turbine and must operate efficiently in either direction. It also provides the mounting point for an array of pressure and temperature sensors which are used to control the pitch of the turbine. Finally it provides protection for the turbine and inner nacelle. The inner nacelle houses the generator, turbine bearings and actuator mechanism. It also houses instrumentation intended to monitor the health of the turbo-machinery.

2. Full Scale Prototype

The concept of conversion detailed in section 1, although making reference to particular instances of equipment, can be implemented in units up to 1MW in size depending on the sea climate and water depth at the intended device location.

A. Structure

Energetech's first full scale device will be installed off the East coast of Australia at Port Kembla by the end of 2004. The structure is a 4-legged guyed structure complete with parabolic wave reflector and oscillating water column. The structure rests on concrete pads on the seabed on 4 legs and is restrained by a 10 leg pre-tensioned mooring system anchored to the seabed with drilled piles. This is shown in Figure 7.

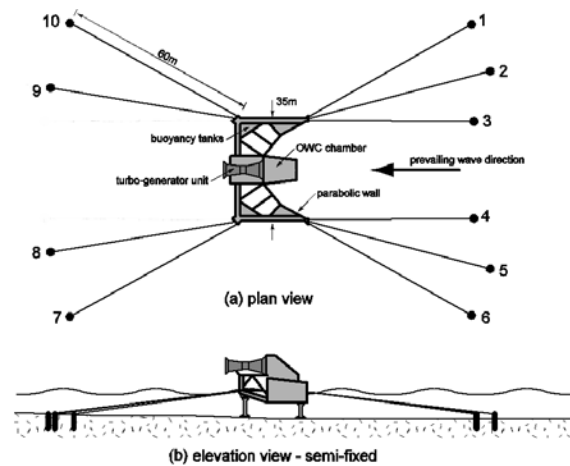


Figure 7 - Mooring arrangement

These legs are telescopic and are lowered into place after the device is launched. Once installed, the structure is effectively fixed to the seabed. It is an all steel design weighing approximately 450 tonnes. In plan view, the structure is approximately 36m wide and 25m long. At its tallest point it is approximately 12m above mean sea level with the main structure extending 4.5m below mean sea level. The structure is designed to incorporate two 20ft containers onto its equipment deck level which is 7m above mean sea level. These are intended to house the electrical control room and mechanical stores. Also mounted at this level is the diffuser and turbo-machinery. All these elements can be seen in Figure 1.

B. Turbo Machinery

The turbo-machinery for the Port Kembla project is as described in section 1. There is a shut-off valve, in this case hydraulically operated. The diffuser and most of the nacelle is fibreglass. The turbine is a 300kW, 21 bladed, variable pitch, 1.6m diameter, 500RPM Energetech turbine of stainless steel construction. This has been built and endurance tested over a large number of cycles. The actuator will be supplied via a UPS to allow for controlled shut down on loss of mains. The control system will also allow the turbine to be pitched sub-optimally in order to throttle the power input to the generator. Brakes are also incorporated into the design but will not be used under normal operation except for parking.

C. Electrical systems

There are many types of machine available that could couple to the Energetech turbine in the power module shown in Figure 6. For the Port Kembla project a multi-pole squirrel cage inverter controlled induction machine was chosen. There were several reasons for this choice both commercial and technical. Cost, delivery, local supply and support had of course to be considered. Technically, this system was chosen for its flexibility, controllability and facility for implementation of various control strategies and control methodologies. It also suited a need in the first full scale device to be tunable in order to match the performance of the various elements of the conversion process under different operating conditions.

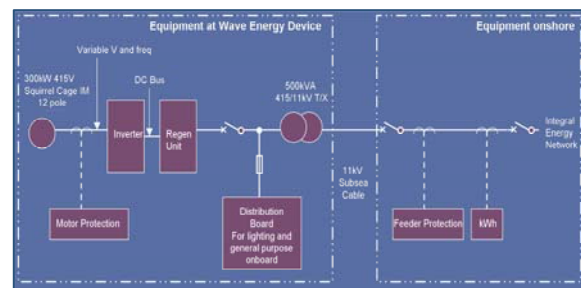


Figure 8 - Single line diagram

A single line diagram of the electrical system is given in Figure 8. This shows the induction generator at variable voltage and frequency feeding back through an inverter system onto a dc link. Another inverter unit known as a

regenerative front-end converts the power back to standard ac. The voltage is stepped up onboard for transmission via a 0.5km submarine cable to the local supply authority. Protection and metering units are located onshore at the link point to the grid.

D. Instrumentation

The first full scale plant will be highly instrumented, and these instruments will be used for the following purposes.

1. Plant safety – of equipment and personnel
2. Process control – normal operation of plant
3. Research – data collection and monitoring used for development of current and future plant

The sensor array includes the following.

- Air pressure and flow
- Turbine torque
- Power train health - vibration and temperature
- Turbine speed
- Generator health
- Actuator position and force
- Wind speed, humidity, atmospheric temperature and pressure
- OWC water elevation
- Structural mooring loads
- Incoming wave height and direction
- Power output and power quality

The sensors will feed into 2 separate data collection systems. The primary control system which consists of a PLC and SCADA unit is feed with all signals required for process control under normal and emergency conditions. A secondary research system consisting of several dataloggers will be used to constantly record and archive all station data and parameters. Both these systems are autonomous and remotely controllable and configurable.

3. Control development

The control of wave energy plant presents the engineer with several unique challenges. Firstly there is generation from a stochastic source. The input to the system varies by wave, by sets of waves by tide and by season. Although average powers and swells can be predicted, the instantaneous nature of the source is random. The station also has time varying multiple sensor input which must be processed. There is also the issues of control of plant under extreme conditions and in a harsh environment. Finally there are some power quality issues arising from the cyclic nature of the source which must be dealt with.

A. Control Philosophy

Within the full scale system, there are a number of process variables which can be monitored, and several physical components on which control actions can be carried out. Figure 9 shows the elements of the physical system which can be controlled and the systems that are required to do this.

These physical systems comprise of the turbine, generator, drive and inertia. The turbine pitch can be

controlled and the generator's reaction torque can be controlled by a variety of voltage and frequency control.

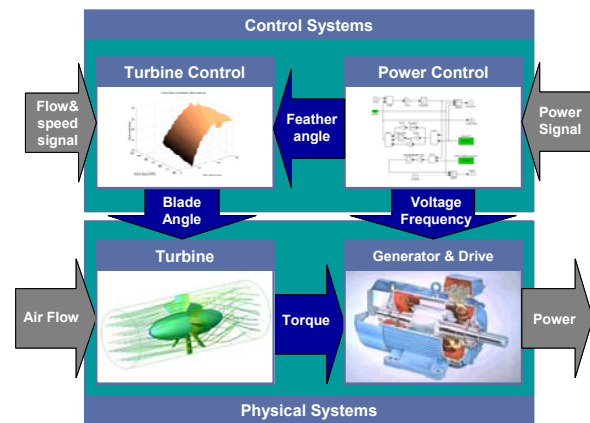


Figure 9 - Control systems schematic

There are several other ancillary systems not shown eg. brakes and valves but as these are not intended for normal mode operation they have been excluded. The control systems should interact with the physical system and also with each other. Figure 9 shows the turbine being controlled by a pitch algorithm and the generator drive combination being controlled by a power algorithm. It also shows all of the systems interacting with each other.

Given that these are the physical systems along with their required controllers, a control philosophy has to be developed which states how each of these systems reacts with each other in order to produce a particular desired station operation.

For the first prototype the control system was required to be robust, efficient and stable. It was also decided that the turbine would be controlled to produce maximum torque, that the inherent inertia would be used to smooth the effect of individual waves and that overall the system should be self tuning to a range of sea states. [6] It has been shown previously that air-driven turbines in unsteady [7] or bi-directional [8] flows can produce more net power if the rotational speed is allowed to vary. It was for this reason that it was decided to actively control the system speed in conjunction with the turbine torque.

The next section shows the development of a wave to wire simulation of the physical systems that was used to test various control options. An example of an optimal turbine control algorithm coupled with a variable speed algorithm will be shown.

4. Simulation

A. Pitch control algorithm for maximum torque

In order to optimise turbine performance in unsteady flows, the blade pitch sequence described in section 1.C must be controlled by a flow-tracking algorithm. An analytical model described in [9] for the full-scale 21-blade turbine was used in the derivation of this blade-

pitch control algorithm. The model was individually run for a complete operational range of conditions including all possible values of inflow axial velocity V_a , rotational speed ω , and blade pitch angle γ . The results were assembled into a 4-dimensional dataset, which included turbine shaft torque as the optimisation parameter. Therefore, the three-dimensional parameter space corresponding to maximum shaft torque was determined.

For implementation in numerical turbo-machine models there are two options. The first involves monitoring the axial flow and rotation speed and then continually updating the blade pitch angle to produce maximum instantaneous power, as determined from the abovementioned parameter space. This is performed at each simulation time-step and the turbine model is solved repetitively as conditions change. The second technique, which is slightly less accurate, involves fitting a two-dimensional analytical function to the maximum torque parameter space, and thereafter evaluating the function as conditions change.

The function-fitting method requires that a reasonably accurate function can be found for the parameter space. Several functions were comparatively tested, including high-order series functions. A continuous function was found which produced the best fit to the data with minimal error without having an excessive number of terms. This was done using several data fitting tools and by performing sensitivity analysis on each coefficient. The function for blade angle, γ , is given in (1) in terms of rotational speed, ω , and axial flow velocity, V_a .

$$\begin{aligned} \gamma = & k_1 + k_2\omega + k_3V_a + k_4\omega V_a + k_5V_a^2 \\ & + k_6\omega V_a^2 + k_7V_a^3 + k_8\omega V_a^3 \end{aligned} \quad (1)$$

where k_n are constant coefficients. A plot of this function, as fitted to the maximum torque analytical model results, is shown in Figure 10.

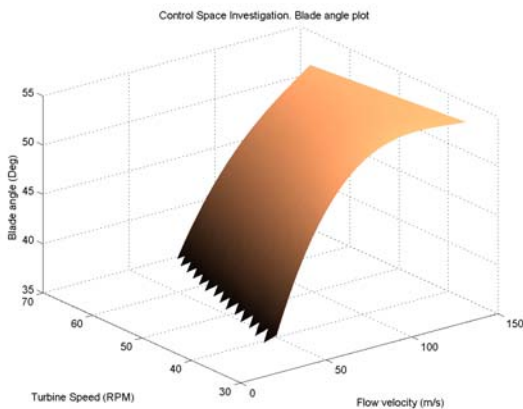


Figure 10 - Maximum torque output control space for 21-blade variable-pitch turbine.

This function shows, that by measuring the speed of the turbine and also the air flow across it is possible to determine the blade pitch angle which will produce maximum torque. This function along with the turbine

model described in [9] can be built into a simulation which will allow for real time torque evaluation and control of the turbine.

B. Electromechanical system simulation in real seas

The next stage in the simulation work was to integrate the turbine and optimal pitch control function into a dynamic real-time model of the whole turbo-machinery power train. This model incorporated several main drive components as well as the control algorithms designed to operate the drive train in an optimal fashion. The simulation of the system is based on the control schematic of Figure 9. The main elements of the simulation are

- Real wave data converted to airflow
- Turbine model
- System inertia
- Blade pitch control model including flip controller
- Induction machine and drive system model
- Self-adjusting variable speed control algorithm

There were several reasons why this model was created but the one of primary importance was the rapid off-line testing of control algorithms, which will eventually be ported over to the real system. To this end the integrated model was developed to be as similar to the real system as possible so that the control inputs and outputs could be mimicked. This would also have the benefit of documenting the predicted range and resolution of various sensors as well as signal tolerances and safe limits for the full scale device.

The real-time wave data were collected over a series of different sea and tidal conditions. The data were then sorted into several sets in order to produce sufficient realistic test data for the model. As the turbine model required an input of axial air-flow as a driving function, the wave data were transformed to this type. On the largest of seas, peak air-flow velocity was of the order of 150m/s across the turbine which matched with the design specification.

The induction machine and drive model were based on an equivalent circuit model of the system scaled to 300kW. This model took into account most of the electrical losses in the system and was calibrated against manufacturers test curves. The variable voltage and frequency drive system model was based on the manufacturers specifications for their equipment. The model also took into account the reactance of the connecting cables and transformer. This allowed the model to give power output as seen from the power authorities metering system.

C. Variable-speed control philosophy

As described in section 3 it was decided to design a variable speed control algorithm and test it in simulation. This algorithm measures variables of power output and system speed and uses these to change both the base operating frequency of the power train and the

instantaneous operating frequency. This results in a gradual drift of the power output in the long term, whereas short-term power fluctuations are reduced by the effect of inertial storage. When the power control system was approaching its constraints of power and frequency it was possible to signal the turbine blade pitch control to sub-optimally pitch the blades, essentially feathering them, and hence throttle the power input.

This meant that feathering would only be used when the power tracking control system reached its limits of operation but remained optimally pitched at all other times. This type of system would provide a stable but variable power output that would work under various sea states allowing the various control systems to interact harmoniously.

The algorithm starts with an initial power demand and a base frequency. This base frequency is the frequency at which the system is attempting to run, but the power fluctuations cause the system to deviate from this as energy is stored and retrieved from the inertia. The amount of deviation from the base frequency determines how much energy is being stored in the inertia. Monitoring this will show whether the system is imbalanced or not, i.e. whether the system is storing too much or too little energy.

An imbalance will create an error signal which either increases or decreases the power demand point so that the system can again balance. For real wave input, the system will never balance, but will be continually searching for the balance. Finding the power balance is essentially tracking the available power input. The more power that is available from the sea then the higher the power demand point will be. The system works by exploiting the difference in time constants, with the frequency control system reacting wave by wave over periods of seconds and the power demand control reacting over tens of seconds. In this way the system can track the average power available.

D. MatLab Simulation

An overall simulation of the physical systems and control schemes described in previous sections was created using Simulink running in the MatLab environment. The top level schematic of this is shown in Figure 11.

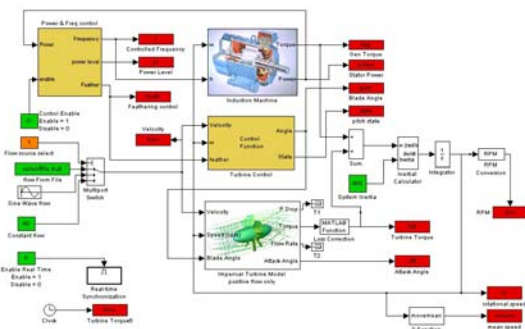


Figure 11 - Control development model schematic

This system was designed to be fully autonomous once activated. However, it was created in such a manner as to allow the user to change some of the characteristics. Varying the parameters does not change the method of control, but merely allows tuning of the system for the desired response. It must be noted that most of the parameters within the system are fixed and have been tuned to respond safely to all the sea states tested.

5. Results

The simulation was tested over a range of sea states and in several different configurations. Tests were conducted with and without optimal blade control and with and without the variable speed algorithm in operation. The results are shown in Figure 12.

With the system just using the optimal blade control, it can be seen that the power output continually drops below zero twice per cycle. This is because without any speed control the induction machine speed only follows its normal torque/speed curve. One of the major problems with this is that the machine and drive, for a large proportion of the cycle are under part load, a condition which makes them inefficient.

The next test was to run the system with speed control and without optimal turbine control. It can be seen that now the power output never falls to its lower levels. There is a small reduction in average power most likely due to the added friction and windage losses which go into the accelerating and decelerating of the turbine. However, it can be seen that the power excursions have been reduced by about 100kW.

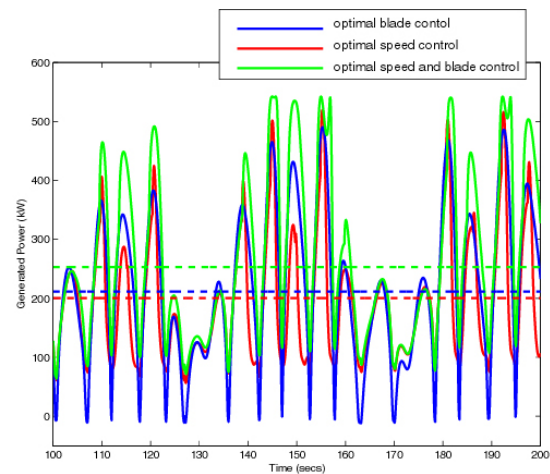


Figure 12 - Results of control tests

Finally a test was performed with both systems operating together. A dramatic increase in overall power can be seen along with the benefit of reduced excursions and no zero power instances. In this case, a large sea has been shown which tests certain extremities of the control algorithm. The system was to start spilling power at 500kW and it can be seen at 155s and 192s that some power has been dropped by the turbine. The feathering control has yet to be tuned as it can be seen that although

it limits the power, it causes a slight dip in output whereas ideally it should limit the power at a constant value.

The system setup with and without speed control was tested over a range of data and a range of different sea states which varied in height, period and average power available. An example output of a much longer part of one of these datasets is shown in Figure 13.

This shows approximately 7 minutes of data. Within the driving function of air-flow, it can be seen that the waves are arriving in groups. This groupiness can be seen clearly in the plot of speed, as it is this variable which governs the base frequency and hence the power level that the control algorithm is operating at. The system can be seen to be adjusting the base frequency to the average power over a period of minutes, whereas the effects of individual waves over periods of seconds are reduced by the system inertia and control algorithm. It can also be seen that the excursions on the power trace exhibit reduced peaks and troughs.

This has the effect of increasing the average power output. In this case the control algorithm has increased the average output by around 10%, even though the original driving sea was not particularly energetic. Similar results were seen throughout the range of data tested.

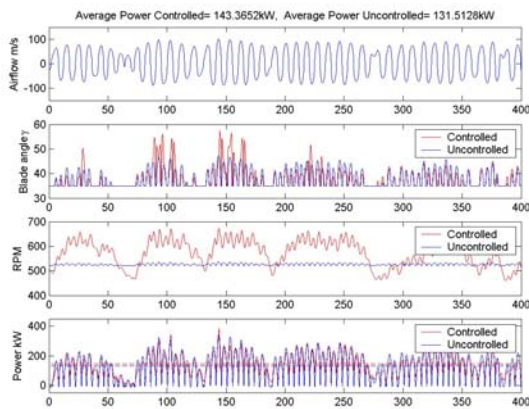


Figure 13 - Power output results

6. Conclusion

This paper has introduced the concept of wave energy conversion utilised by Energetech. It has described the development of this concept and its application in a full scale station.

The power conversion elements and control systems of a full scale station were described and a control philosophy introduced which detailed the normal operation of plant.

This paper has also shown the development of a power train and control simulation. The holistic model shows how optimal blade control and drive control can be combined. A variable speed control algorithm aimed at increasing plant efficiency was described.

Simulations based on real wave data indicate that a power output gain of between 10%-18% can be achieved using optimal blade pitching combined variable speed power control. The results also show that the cyclic nature of the power output has been dramatically reduced which in turn will improve the power quality of the supply to the grid. [11]

Finally, it has been shown that a control feature can be added to throttle the power in more energetic seas, thus increasing the capacity factor of the station over long time periods.

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